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NAVAL AIR PROPULSION TEST CENTER

TRENTON, NEW JERSEY 08628

PROPELLSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

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TURBINE ENGINE DIAGNOSTIC DEVELOPMENT

PHASE I REPORT

NAVAIRSYSCOM AIRTASK A3305360/218B/2F0043301

Prepared by:

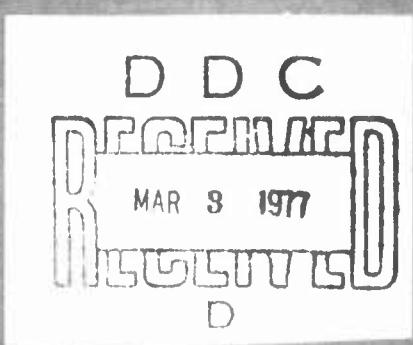
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INTRODUCTION

The Naval Air Systems Command (NAVAIR) (AIR-330) authorized the Naval Air Propulsion Test Center (NAPTC) to develop and demonstrate a prototype Turbine Engine Diagnostics System by full-scale engine test. This work, under Work Unit Plan NAPTC-624, is one element of exploratory development under AIRTASK A3305360/218B/2F0043301 of 25 June 1971 (Appendix A).

The Turbine Engine Diagnostic Development (TEDD) Program is the NAPTC effort for a Navy program to develop an Integrated Engine Diagnostics and Displays System (IEDDS) for advanced aircraft of the 1980-85 time frame. The IEDDS will be designed to replace conventional cockpit gages and will provide output messages pertaining to energy management and diagnostics. The TEDD system will include a visual display of engine performance and diagnostic messages and will be ready for advanced development funding in FY 1975. The system should have the capability to recall and display abnormal conditions on the ground for use by ground maintenance crews. Additional work should be possible on the ground to show trends for the particular engine and to aid the ground crew in isolating the fault to a line-replaceable unit. A successful system will be able to replace conventional maintenance procedures with a maintenance-as-required system.

During FY 1972, NAPTC accomplished Phase I of the program, which consisted of generating and testing a computer program which would track a TF30-P-408 engine at sea level conditions and output diagnostic messages. A unique vibration monitoring system was used, as well as new type transducers for oil quality and speed sensing.

Phase II will further refine programs and include engine tests with a ram inlet installation. Computer programming will be developed for a high resolution cathode ray tube (CRT). Parameter trending will be implemented as well as fault matrices.

Test details for Phase III are not fully defined but will refine the program so it will operate through the complete operating envelope of an advanced engine. Phase III will also define the split between diagnostics done airborne and diagnostics done on the ground. Concurrently with Phase III testing, a specification for a Request For Proposal will be formulated for the IEDDS.

SUMMARY

A turbine engine diagnostics system was designed, implemented and tested on a TF30-P-408 engine. The test was run with a bellmouth at sea level conditions. Inputs for the system were obtained from a high speed data system using 50 parameters and operated under computer control. Diagnostic messages were displayed on a low resolution CRT and other outputs were obtained from a line printer and a digital plotter. A flow chart for a computer program was made which would track engine operation from Start through Idle, Acceleration (slow or fast), Part Power, Intermediate, Deceleration, Part Power, Idle, and Coast Down. The computer program was written in Fortran IV language for an XDS 9300 computer with 32K memory, three tape systems, and a random access drum of 0.5 megawords. The capability to check nine performance parameters against stored curves was programmed, as well as 62 messages. The vibration monitoring system developed by General Electric Company (G. E.) was programmed to check 70 mechanical items. Base line values for these items were determined. Sufficient digitized raw data was recorded so additional work could be done on the program without running the engine. Also,

analog data from the vibration pickups was recorded for Phase II use. Engine oil was monitored for quality by three different devices and checked against spectrometric oil analysis. The engine was run 11.2 hours with the diagnostics program and 17.9 hours for performance calibrations. The recordings taken during engine runs were used for approximately 10 additional hours of simulated engine running for program debugging. Engine oil was monitored for 98 hours by utilizing engine time accumulated on succeeding projects.

CONCLUSIONS

1. The Phase I objective of diagnosing engine problems was accomplished in the categories of Hot Starts, Pattern Factor Distress, Hot Section Distress, Oil System, Vibration, and Performance by displaying at least one message for each category.
2. Thirty-four of the 47 diagnostic messages programmed were demonstrated by causing messages to appear on the CRT screen for a legitimate reason.
3. The diagnostic program successfully tracked engine operation from Start through Idle, Acceleration, Part Power, Intermediate, Deceleration, Part Power, Idle, and Coast Down.
4. The false alarm rate must be reduced.
5. Plotting time for engine performance was excessive.
6. The G. E. vibration system was successfully operated by the computer. Thirty of 70 programmed experiments were valid. Problems occurred in the area of tachometer signal stability and communication between the transducer and the rotating component.
7. The transducer constructed for zero speed indications worked satisfactorily, but could not withstand normal gear box temperatures.
8. The ENVIRONMENT ONE oil monitor worked satisfactorily. However, before engine start-up and before engine oil flow started, high indications of oil transmissivity could occur, depending upon where the rotor of the unit stopped.
9. The TEDECO magnetic plug type oil monitor satisfactorily extracted chips from the engine oil.
10. The K WEST debris monitor was ineffective because of its location downstream of the main engine filter.
11. The oil level system was sensitive to engine rpm and vibration.
12. Accuracy of the hot section distress accumulator could be increased by measuring turbine blade temperature.

RECOMMENDATIONS

1. That the diagnostic program be improved so it will track the engine with any power lever manipulation throughout its operating envelope.
2. That the project be continued to establish more accurate diagnosis and reduce false alarms. This will require the use of fault matrices, data validity checks, refinements in limits, signal smoothing, and trending.
3. The speed sensing system be improved. Investigation should be made into the possibility of using a signal from an optical pyrometer for speed sensing.
4. That the ENVIRONMENT ONE oil monitor outputs be automatically shut off until oil flow is sensed.

5. That the TEDECO oil monitors be installed in at least three of the engine scavange lines.
6. That the K WEST debris monitor be checked in a location upstream of the main engine filter, and be considered for integration of the concept into the main engine filter.
7. That accelerometers be installed internally on the main bearings of engines so the bearing monitor feature of the G. E. vibration system can be utilized.
8. That extensive use of a high resolution CRT be made to display additional messages and graphics of engine operation.
9. That an optical pyrometer be used to furnish the input to the hot section accumulator for blade life.

DESCRIPTION OF EQUIPMENTA. Engine

The TF30-P-408 engine was selected as the test vehicle on the basis of similarity to the advanced engine of IEDDS and availability. The TF30-P-408 engine is a twin-spool, axial flow, non-afterburning gas turbine engine. Major components include a 9-stage low pressure compressor unit, including a 2-stage fan; a 7-stage high pressure compressor unit; can-annular burner section with 8 through-flow combustion chambers; a single-stage high pressure turbine wheel with air-cooled blades and vanes; and a 3-stage low pressure turbine unit. Engine and fan air inlets are common, and both airflows are combined for discharge through a fixed area, convergent jet nozzle. The nominal engine rating at sea level static Intermediate power conditions is 13,400 pounds at 256 pounds per second total airflow, with a compressor pressure ratio of 18.8:1 and a bypass of 0.99:1. The exhaust nozzle area is approximately 3.65 feet².

The engine has an acceleration bleed system which vents air from the 12th stage compressor into the fan duct via bleed valves in the compressor case. This system was designed to increase compressor stall margin at low power. It operates as a function of low pressure compressor discharge pressure (P_{S3}) and engine inlet pressure (P_{T2}), with an override signal from the fuel control to open the bleeds during rapid decelerations.

B. Installation

The TF30-P-408 test engine, S/N P-665158, was installed in sea level test cell 1W on a movable, flexure supported thrust stand (Figure 1). Outside ambient air entered the test cell through an overhead door and turning vanes, and was supplied to the engine through a standard TF30 test bellmouth and screen attached to the engine inlet. The engine exhaust gases were vented to the atmosphere through an ejector and exhaust stack.

Both high and low pressure compressor bleed air manifolds were installed on the engine, with regulating valves and airflow measuring stations.

A standard A-7 aircraft constant speed drive and generator were installed to load the accessory gearbox for vibration analysis.

A manual 12th stage bleed open/closed override system and false burner pressure signal to the fuel control were utilized to obtain desired operational malfunctions.

The instrumentation diagram is shown on Figure 2.

C. Data System

1. Pressure transducers were of the unbonded strain gage type of 1/2 percent accuracy.
2. Temperature transducers were thermocouple, both Iron Constantan and Chromel Alumel.
3. Signal conditions were B & F type 1-700 (see Figure 3).

4. Frequency to DC converters were VIDAR model 323.

5. The multiplexer, A/D Model 120-117, is a packaged unit made by DATUM, Inc., incorporating a solid state addressable multiplexer with differential input, a sample and hold, a 12 bit plus sign A/D, and an addressable amplifier with eight programmable gains from 1 to 1000. Sampling rate is normally 10,000/second. For this application, 10 samples were read, the lowest and highest discarded, and the remaining eight averaged. Gain accuracy is ± 0.1 percent of full scale. Daily two-point calibrations are required to achieve this accuracy. A list of parameters is shown on Figures 4 and 5. The multiplexer and analog-to-digital converter were located about 300 feet from the test cell and connected by shielded twisted pair wire.

6. The computer is an XDS 9300 with 32 K of memory (24 bit word), three tape systems and a random access drum of 0.5 megawords. It included a DELTA DATA Systems Model Delta 1 CRT display system programmed for alphanumerics of 24 rows of 40 characters.

7. A Fischer & Porter steady-state data system permanently installed in the cell was used to establish base line performance values for the engine. It was also used occasionally to check various parameters at steady-state of the diagnostic data system.

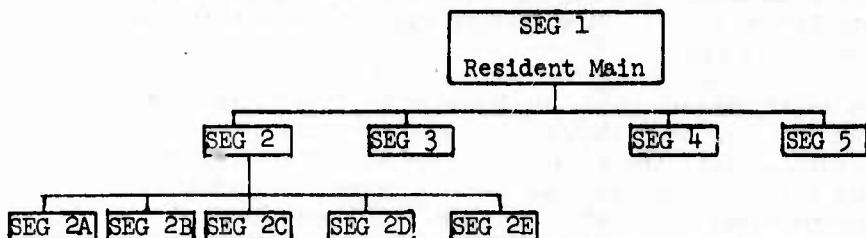
8. A 14-channel analog tape system was used to record vibration. The unit is a PRECISION INSTRUMENT Model 2114 unit. It uses one-inch tape and was run in its FM mode at 15 in./sec., which gives a frequency response of 0-75K Hz. The parameters recorded are listed in Figure 6.

D. Program

The TIDD computer program was structured to read engine data, process this data in a prescribed way, analyze, and then output a diagnostic message. It consisted of a main program which could call on 23 different options, each one of which would perform some specified task. The main program, along with some data files, was resident during the running of the program.

The input portion of the program read data from either one of two systems: (1) The Fischer & Porter Data Acquisition steady-state system, and (2), the DATUM low level multiplexer. The Fischer & Porter system was read when an on-line listing or display of computed steady-state data was desired, such as determining base line calibrations. Options from the main program enabled a CRT display of 34 calculated parameters and/or a listing on the line printer of 51 calculated parameters. CRT messages are listed in Appendices B1, ~~and B3~~. A picture of the CRT is shown on Figure 7. The other mode of input was the reading of the Datum. This consisted of the reading and storage of 50 channels of data approximately every 80 milliseconds. The 50 channels of data were read and entered into a buffer area of 2,000 floating point words which, when full, was dumped to tape for permanent storage purposes. Thus, the data recorded could be reprocessed at some future date. The Datum was also read on command from the diagnostic section of the program.

All coding was done in XDS Fortran IV. The operating system, together with flow chart logic, forced a program flow as shown in Figure 8. The complete program consisted of nine overlay program segments, any one of which could be called at one time into the Central Processor Unit (CPU) from the Random Access Drum (RAD). The structure of the main resident program and overlays is as follows:



SEG 1: Main program plus labeled common data storage and labeled common data handling routines.

SEG 2: Specialized data handling routines. Common arithmetic routines for sub-segments.

SEG 2A: START routine.

SEG 2B: IDLE routine.

SEG 2C: PART POWER routine.

SEG 2D: ACCEL, DECEL routines.

SEG 2E: INTERMEDIATE routine.

SEG 3: Steady-state data handling and computations.

SEG 4: Utility routines, listings, displays, etc.

SEG 5: Plotting routines.

Timing references were provided by a real time clock addressable via an interrupt in 1/60 second increments.

The diagnostic section of the program consisted mainly of reading the Datum system under program control and, with this data, checking for limit or rate exceedances and periodically inspecting specified parameters to define a new operating routine. If the conditions of the new routine were met, a new overlay was called by the operating system and essentially the same process repeated. Any diagnostics that did occur (as well as where they occurred) were output on the CRT and on the line printer.

The output section of the program made use of a CALCOMP 565 plotter with which any raw data or calculated parameter could be plotted against either time or some other parameter. Magnetic tapes were continually updated with new data for each mission, and utility print routines were available for detailed listings. Figure 9 shows computer hardware configuration. (Appendices C-1 through C-13 show flow charting for the program.)

E. Oil System

Figure 10 is a schematic of the high pressure side of the TF30-P-408 engine lubrication system, where most of the oil diagnostics were performed. The location of three oil monitoring units is shown in the supplemental oil cooler discharge line: (a) The ENVIRONMENT ONE oil monitor transducer; (b) The TEDECO magnetic chip detector; and (c) The K-WEST debris monitor. The section of oil line containing these units is shown in Figure 11.

First in line is the ENVIRONMENT ONE unit, whose operating principle is based on light scattering and light attenuation techniques. There is also a flow rate indication, but in this installation the oil flow reading was not valid when the low oil temperature bypass valve was open.

The transducer is approximately three inches in diameter by five inches long and weighs 2.6 pounds. Since it is mounted in the high pressure side of the oil system rather than in the scavenge line, the effects of free air in the oil are minimized because most of the air is dissolved. As the oil passes through the transducer, it causes a rotor to turn. The rotor contains fluid passages and optical references which are alternately placed in an optical system as the rotor revolves. In addition to providing the reference function, the revolving rotor causes the light received by the photo sensors to be chopped, so that AC amplification, which eliminates stray light and dark current effects, can be employed. The optical paths utilize sealed fiber optics to conduct the light into and out of the oil and to produce a light beam parallel to the axis of the rotor. Because of the collimating properties of fiber optics, no lenses are required. One photo sensor is mounted radially so that it views the light beam at 90° to provide the scattering output. The attenuation sensor views the axial component of transmitted light. The output of each sensor is a series of pulses alternating between reference and signal. These are fed to a signal conditioner which, in effect, computes the ratio of signal to reference amplitudes. Since the same light source, windows, and sensor are used for the reference and signal, all variations in these components are canceled out. With the rotor stopped, the oil flow cross-sectional area is maintained at least as much as that of the oil line itself in order to minimize flow restrictions. Figure 12 shows an internal view of the transducer.

The oil then flows past a sensing type magnetic chip detector. This detector is a developmental model and similar in physical dimensions to TEDECO Model A-7208R, except for the electrical connection. However, instead of detecting the presence of magnetic material by measuring the electrical resistance across the magnetic gap, it utilizes the Hall Effect to give a quantitative reading of the presence of ferrous material even if it does not completely bridge the magnetic gap. The unit was mounted in the bottom of a cyclone type separator. (See Figure 13.) The unit is slightly temperature sensitive. A temperature correction was programmed into the diagnostic program.

The oil then flows through a K-WEST Debris Monitor. This monitor utilizes a sensing grid woven in a unique pattern. Transparent polyester filaments which serve as insulators are interwoven with stainless steel conductors. These elements are locked together with a third small diameter, stainless steel wire which also greatly improves the contact surface when debris is impinged on the grid by the oil flow. A proprietary method of interconnecting each conductive strand of the screen allows the detection of conductive debris as it progressively shorts out successive adjacent wire pairs. A solid cone at the downstream end of the screen deflects oil through the screen. As debris collects along the interface of the screen, the flow will gradually divert itself to the remaining open area and thus randomly distribute the debris over the entire area of the sensor. Any debris that is electrically conductive (both ferrous and non-ferrous) will be detected.

The effective reduction of electrical resistance as buildup occurs is read out on the data system. Figure 14 shows the unit.

The sequence of installation of oil monitors was chosen so that the first unit would look at the oil, the second would remove ferrous material, and the third would remove remaining material. Thus, a diagnosis of ferrous or non-ferrous material could be made.

In addition to the above three units, the pressure pulses at the outlet of the main oil pump were converted to electrical signals and sent to the G. E. vibration system for analyzing.

Oil pressure, oil temperature, oil level and breather pressure were also monitored.

Oil system diagnostics were performed as per the flow chart in Appendix ~~25~~ C5

F. Tachometers

The engine diagnostic logic required that the speed of both engine rotors be measured down to zero speed. The zero speed requirements exists due to the fact that the first turning of each rotor during crank must be sensed to measure start-up rotor frictions, and the final coast time to stop must be sensed for an indication of coast-down rotor friction. To this end, a proximity type pulse generator was chosen which sensed teeth on a gear driven by the tachometer pad. The device is shown on Figure 15. It allows for driving the conventional three-phase tachometer from the same pad. The device, made by AIRPAX, utilizes the Hall Effect on a solid-state device to either produce a high (5 volt) or a low (0.1 volt) output, depending on proximity to a gear tooth. It does not depend on rate of change of proximity and can, therefore, be used as a static device. The output was sent to the DATUM system (Channels 23 and 24 for N_1 and N_2 , respectively) for slow speeds down to zero and through a frequency to DC converter to Channels 25 and 26 for normal speed indications. The pulses were also sent to a variable time base counter for display of speed in rpm. The number of teeth chosen for the pulses generator was 35. This was done as a compromise between a high frequency limit and a convenient pulse rate for the G. E. vibration system.

G. Vibration System

An important part of a diagnostic program is the vibration routine. The system used at this facility is an outcome of a series of development contracts let to the G. E. Company. The first contract was let in 1962 (Reference 1) and consisted of studies. Succeeding contracts included bad parts testing at Quonset Point, Rhode Island (Reference 2) and development of a digital system using the frequency of occurrence of binary words technique (FOBW). After some testing at Boeing Vertol on a CH47 helicopter transmission (Reference 3), the FOBW technique was discarded in favor of an impact index system for bearings and a digital comb filter for gears. This system was first used on a TF34-GE-2 at NAPTC during 1971 (Reference 4). This piece of gear was then adapted (Reference 5) to computer control and used for the subject testing on the TF30-P-408.

The vibration system was built by G. E., Binghamton, New York (See Figure 16). It was originally built for the TF34-GE-2, but since the system is easily converted to any engine by changing ratios and limits, there was no problem in using it on the TF30-P-408. All switching operations for different experiments are done by solid-state switches, thereby enabling this function to be performed by a computer. An interface to perform the switching function and the work necessary to determine switch settings for the TF30 experiments was purchased from the manufacturer for this test. A list of experiments is shown in Appendix D, pages 1 through 4.

Input requirements for the analyzer are tachometer signals from N_1 and N_2 , six accelerometer signals, and power at 115 volts AC 50 to 400 Hz single phase 80 watts. The unit has the capability to accept 12 accelerometer signals. A foreign object damage detector made by G. E. was also used. This unit utilizes the signal from an accelerometer mounted on the front frame of the engine. It processes this signal for peak value and compares it to a manually set limit. Variable time constants and a range of inputs are available. The alarm light is a one-shot system and requires a manual reset.

Accelerometers were ENDEVCO Model 6222 M3 and were mounted in the following locations:

| <u>SENSOR NO.</u> | <u>STATION NO.</u> | <u>LOCATION</u> | <u>POSITION (O'Clock)</u> |
|-------------------|--------------------|------------------|-------------------------------|
| 1 | - | gear box | 6:30 |
| 2 | - | gear box | 4:30 |
| 3 | 2 | fan frame vert. | 12:00 |
| 4 | 2 | fan frame horiz. | 8:30 |
| 5 | 4 | diffuser case | 1:00 |
| 6 | 5 | turbine case | 6:00 |

H. Signal Processors

The analyzer contains signal processing electronics to evaluate four classes of malfunctions in an engine. These are: (1) Bearings; (2) Mass unbalance; (3) Gears - local defect; (4) Gears - gross defect.

To evaluate each malfunction type, various signal processors are employed. An important processor used in three of the four malfunction classes is the digital comb filter which will be discussed separately below.

Digital Comb Filter - The digital comb filter is a time-averaging device of 256 discrete points. The time-averaging feature tends to cancel the noise. The comb filter is synchronized with a rotating member so that each of 256 points examines the same point on a rotating member. The filter has responses at its tuning frequency and integer multiples (harmonics) of it. Any signals or noises which are not exactly integer multiples of the tuning frequency will be rejected. The significance of this type of filtering can be seen when a vibration signal from a gear box is applied to the filter. This signal will consist of the sum of all gear box shaft and meshing vibrations. By tuning the filter to a gearshaft frequency, only the shaft and its gear meshing frequencies are passed through the filter, since the number of teeth x shaft frequency is a shaft harmonic.

Bearing Malfunction Processor - The bearing malfunction discriminant processor evaluates the Impact Index of the acceleration signal from a bearing housing. The Impact Index is a normalized dimensionless quantity whose value is indicative of the incipient bearing malfunction. The Impact Index value is one-half the ratio of the peak signal level to its average level. An Impact Index for a normal bearing will range from 2 to 3 and, during spall initiation, from 3 to 4. As the spall increases in size (but is still relatively small), the Impact Index may increase to 8 to 10. Beyond this, with increasing spall size, the Impact Index will decrease due to the increase in average acceleration. The Impact Index discriminant for normal bearings is not a function of engine speed; i. e., it will remain between 2 and 3 over the entire engine operating range. For a bearing with a malfunction, the Impact Index may increase by up to 30 percent with increasing engine speed. Full scale on the indicator is an impact

index of 10. The bearing malfunction feature was not programmed as an experiment for main bearings because there was insufficient communication between the bearing and the accelerometer mounted on the external part of the engine. Internal accelerometers are required.

Mass Unbalance Processor. - The mass unbalance discriminant processor is a narrow band tracking filter which selectively filters vibration energy associated with the mass unbalance of a rotor system. The output is displayed as a displacement on a meter calibrated from 0 to 100 percent full scale, where full scale is equal to 10 mils double amplitude. The signal is first filtered to accept frequencies in the 10 Hz to 400 Hz band. It is then filtered by the digital comb filter, which is tuned to either once per fan or core frequency. The output of the comb filter now represents the acceleration associated with the rotor mass unbalance. A double integration then yields the displacement associated with the rotor mass unbalance. To obtain a signal suitable for display, the displacement signal is average detected and displayed on a meter calibrated to read peak-to-peak values. Experiments 60-67 give mass unbalance of fan, compressor and turbine of N_1 and N_2 rotors.

Local Gear Defect Processor. - The local gear defect discriminant processor evaluates the Impact Index associated with a given gear mesh vibration signature. Local defects on a gear consist of spalled, deformed, or cracked teeth.

A normal gear in mesh will generate a sinusoidal vibration at the gear meshing frequency. When a local defect is present on a tooth of the gear, a transient vibration will be generated each time that tooth meshes. The level of the transient will be considerably higher than the normal meshes. This type of signal can easily be discriminated by an Impact Index measurement. Since, in practice, a single gear mesh vibration is mixed with other mesh vibrations and noise, this mesh must be extracted from the total signal before its Impact Index may be evaluated.

The discriminant measurement is implemented by tuning the digital comb filter to the gearshaft frequency of interest. This will allow integer multiples of the shaft frequency to pass through the filter while rejecting all other signals. The modulation will be passed through the filter. The measurement which is then made on the signal is the ratio of the modulation amplitude to the carrier (gear mesh) amplitude yielding the modulation index, which ranges from 0 to 100. This is a dimensionless parameter.

The AC portion, which contains the modulation, is low pass filtered to allow only the modulating frequency to pass. The low pass filter is programmable so that the filter cutoff may be set for various gears and various engine power settings. The output of the low pass filter is then peak detected and displayed on the output meter. Experiments Numbers 25 to 53 were programmed for gross gear defects in the gearbox.

Experiment 70 is to test for abnormal oil pressure fluctuations from the output of the oil pump. It uses the same experiment setup as Experiment 14, Main Oil Pump Drive, except it uses the output from a fast response pressure transducer on the output of the oil pump.

Experiments 80 to 95 check for modulation of blade passage frequencies of the compressors and turbines and would indicate blade damage.

The G. E. vibration system was programmed so it could print out the result of each experiment and it would asterisk each parameter over one-half scale on the

output. The asterisked parameter would also appear on the CRT with its corresponding experiment number. Accessory gear experiments were automatically skipped if the alternator was loaded to less than 40 amps per phase.

I. Hot Section Life Accumulator

C 8

This system was implemented by using the computer, flow chart (Appendix B8) and the curve shown on Figure 17. The calculation assesses hot section life from a thermal fatigue standpoint. The program would calculate T_5 by adding compressor temperature rise to T_7 , applying a correction factor, and enter the stored curve at this temperature. It would then read life in seconds, take its reciprocal and multiply by the time between present reading and previous reading. It would then increment the accumulator with this value. A total of 100 percent would mean that all useful life is used up.

J. Ultrasonic Microphone

These microphones are generally used to detect gas leaks. They heterodyne the signal with a local oscillator to produce a difference signal in the audible range. In the application for this program, a microphone made by Techsonics (Son-Tector Model 112) was used with a contact probe in an attempt to pick up vibrations in the vicinity of the center main bearings, which were above the normal vibration frequency of the accelerometers (2000 Hz). A picture of the installation is shown on Figure 18.

METHOD OF TEST

The engine was calibrated under sea level conditions. See Figures 19 and 20. Operation of the engine to check each program change would become very expensive. Therefore, engine data was recorded for a cycle of Start, Idle, Acceleration, Intermediate, Deceleration, Part Power, Idle and Coast Down. This data was then used to debug the program. Periodically, the program was checked on a running engine. Due to slight differences in the program for reading raw data from tape and for reading data from the engine, there was no assurance that all bugs were removed from the program if the program worked from tape. The engine test, therefore, was required for final proof of the program. Also, one engine cycle was not sufficient for ascertaining whether the program would work. Slight differences in power lever manipulation and other variations in the cycle could cause the program to hang up in certain cases.

A final test was run to demonstrate the various malfunction messages. Of the 47 possible fault messages, 34 were demonstrated. They were demonstrated by an actual engine limit exceedence, a false signal, or by lowering the limit. The CRT listing in Appendices B1, B2 and B3 has been footnoted to identify messages demonstrated and how they were obtained.

Any parameter could be plotted against time. This capability was used to check for noisy or inaccurate signals. The 14-channel analog tape system was run to record vibration data. The data will be used to verify results of the G. E. vibration analyzer. Speeds, fuel flow, and time were recorded for correlation purposes.

DISCUSSION OF RESULTS

The program would track the engine in the sequence of Start, Idle, Acceleration, Part Power, Intermediate, Deceleration, Part Power, Idle, Coast Down, but only in that order. This is due to the program flow as shown on Figure 8, page 50. This caused no difficulty at this time and will be remedied for Phase II by incorporating mode recognition logic. The demonstration of the diagnostic messages showed that the system worked for the inputs used. These fault inputs were purposely made large, since the main purpose of the test at this time was to test the logic. For example, many faults were simulated by electrically disconnecting the appropriate transducer. The limits will be narrowed down when smoothing techniques, the fault matrix, and necessary corrections are applied.

A consideration when writing the program was to enable easy changing of limits and other constants. To this end, a constant array of 300 items was provided for. About 100 were used for the present program. The constant array will also help in adapting the system to another engine. However, engines differ in the manner in which fuel is scheduled, stall prevention (bleed or variable guide vanes), nozzle area changes, afterburner operation, etc. These differences will have to be taken care of by logic changes and different calculations.

It is apparent that if all shortcomings are remedied for the sea level installation, additional problems will be encountered in the ram installation of Phase II. Furthermore, when the system is finally flown in an aircraft, numerous additional problems will be encountered. As an example, during a catapult or arrestment, performance changes might become evident. Also, if a ground check is made under high or low humidity conditions, the trim may change. Whether an inlet screen is used or not used during a ground run will affect performance. A host of oil problems will occur during negative "G" flight. All of these contingencies can be taken care of, but it will require additional programming. An alternate solution is to monitor important parameters, such as T_5 and vibration, and perform diagnostics only under certain prescribed conditions.

The hot section life accumulator at this time attempts to assess hot section life from a time temperature standpoint and does not address stress rupture or low cycle fatigue. The points were obtained from NAVAIR manual 02B-10FB-6-1, paragraph 10-48, Section X, Table 10-4. An improvement to the system would be to add speed and low cycle fatigue inputs, but the state of the art is not sufficiently advanced to do this at present. The optical pyrometer to be used in Phase II will increase the accuracy of blade temperature measurement and, therefore, assessment of hot section life. It is anticipated records of individual blades can be kept.

Figures 21, 22 and 23 show plots of inlet pressure (P_{T2}) vs Time, P_{T7} vs Time, and N_2 vs Time. It is readily seen that the noise in EPR can approach the band width of acceptable values. A smoothing technique will have to be applied in this case to obtain acceptable data.

The three oil quality transducers were compared to the Navy Spectrometric Oil Analysis Program. Figure 24 is a plot of results of the analysis vs the 97 hours that this engine was run, and shows the change of light transmissivity and light reflectivity vs engine time. No deterioration of the oil was evident. Twenty-five quarts of oil were added during this engine operation. Oil level varied with engine rpm (see Figure 25).

The TEDECO oil unit was found to be inoperative on completion of test due to an error in electrical hookup. The unit had collected some chips which were evidently from new plumbing used to incorporate the auxiliary cooler and oil monitoring devices. When the system was correctly connected and checked external to the engine and at room temperature, the collected chips caused the meter to read 24 percent of full scale.

The G. E. vibration system programming was changed from normal for this test, so that the program would do all 72 experiments before continuing the diagnostics. This was done so that results of all experiments would appear together on the list from the line printer. Time for the vibration program was about one and one-half minutes. In the normal mode of operation, other diagnostics would be done while the vibration experiments were in progress. An experiment list and their readings at Idle and Intermediate are shown in Appendices ~~C~~ through ~~C7~~.

D

The data presented in these runs indicate levels predicted from the theory that was used to build the detection circuits except for those experiments concerned with overall or gross gear defects. The problems with these experiments could arise from several areas. The first of these is an unstable tachometer signal. To do the analysis for gross gear defects, a chain of multiplier-divider networks must be used to extract the signal, and then analyze it at the gear shaft fundamental frequency. If the ratioed tach signal does not constantly track gear shaft speed a modulation occurs which shows up as a full-scale meter deflection.

A second problem that may occur is a lack of signal at the detection circuit. This is the result of poor communication between the sensor and the shaft being analyzed. The full-scale deflection occurs due to non-associated transients that reach the detector circuit. The gearbox was loaded with an alternator to 25 KW to increase the signal to noise ratio for gearbox components. Load values under 40 amps per phase caused the computer to ignore gearbox experiments.

These problems can be solved by several means. The tachometer multiplier-divider circuits can be slowed by decreasing the slew rates of the phase locked multiplier. This correction must be limited so that the tracking ability of the multiplier will not be impaired. An attempt at this correction was made during the diagnostic program. This correction gave improved results on all experiments except those concerned with gross defects. Another fix for these problems would incorporate a detector circuit to indicate a low level signal and show zero output to the meter circuit. The obvious fix is to obtain a tachometer signal more representative of rotor speed.

Aside from this one problem area, the vibration analyzer represents the first automated system that is self-sufficient. Its unique dimensionless measurements insure valid detection without the need for elaborate calibration. The analyzer is versatile, and programmable so that any part of the engine may be investigated. The system is fully automated and the outputs do not require elaborate analysis to indicate a decision.

The pulse generators used for the tachometers worked satisfactorily, except for their temperature limitation. The accessory gearbox of the engine normally ran hotter than the limit of the unit. Therefore, it was required to place a heat barrier between the tachometer pad on the gearbox and the unit. The N_1 tachometer pad on the TF30 engine is located in the bullet nose and ran cool enough in this installation. However, when bullet nose anti-icing air was turned on, it overheated the pulse generator. The one-quarter inch square drive of the tachometer drive was found to have 10.8° of backlash. This may not appear to be

excessive, but if it is related to phase shift for a 35 tooth gear it amounts to over 360° in phase shift. The phase shift was verified by oscilloscope observation. The phase shift causes problems for the phase-sensitive oscillator/multiplier in the G. E. vibration analyzer. It explains the trouble in obtaining a speed lock condition and is a contributing cause for those gross gear defect experiments which were invalid.

It is normal for present day solid-state devices to cease functioning at 300°F . If this device cannot be made to operate in this environment, an alternate is to use an optical system with perforated disk, or a high frequency magnetic device which is modulated by gear tooth passage.

Recordings from the ultrasonic microphone were obtained. The data were not displayed or reduced at the time of report writing.

APPENDICES

| <u>APPENDIX NO.</u> | <u>DESCRIPTION</u> | <u>Page</u> |
|---------------------|---|-------------|
| A1 | Work Unit Plan NAPTC-624 of 8 June 1971 | 16 |
| A2 | Authorizing Letter of 25 June 1971 | 22 |
| B | CRT Messages | 25 |
| C1 - C13 | Flow Charts | 27 |
| D | Experiments | 40 |

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*Naval Air Propulsion Test Center
Trenton, New Jersey 08628*

WORK UNIT PLAN

Date: 8 June 1971

| | | | | | |
|---|--|-------------------------------|-------|--|--|
| 2. Title Turbine Engine Diagnostics Dev. | 1. Sponsor's Assignment No. | 9. Center Ident. NAPTC-624 | | | |
| 5. Program Manager/Code D. H. Williams/AIR-330 | 3A. Element/Appropriation Cat. 6.2 | 3B. Sponsor NAVAIR | | | |
| 6A. Technical Agent/Code K. H. Guttmann/AIR-330C | 10A. NAPTC Liaison/Code/Phone E. Lister/ATL-P X-391 | | | | |
| 6B. NAVAIR Liaison/Code R. R. Brown/AIR-536B1 | 10B. Principal Center Investigator Name/Code/Phone P. F. Piscopo X-391 | | | | |
| 8A. Other Participating Sponsors | 7. Kind of Summary Proposed | | | | |
| 8B. Estimated Completion Date Continuing | 4. Prior Identification | | | | |
| 11. MANPOWER AND COST ESTIMATES | CFY-1 | CFY | CFY+1 | | |
| a. Technical Man-Years | | - | 0.8 | | |
| b. Total Direct-Labor Man-Years | | - | 5.0 | | |
| c. Total Labor and Overhead \$(K) | | - | | | |
| d. Materials and Travel \$(K) | | - | | | |
| e. Major Procurements/Contracts \$(K) | | - | | | |
| f. Planning Estimate \$(K) | //////// | - | | | |
| g. Funds Available \$(K) | | - | - | | |

12. OTHER INFORMATION

a. Background: The ideal engine monitoring system would provide an exact determination of engine condition. This implies both mechanical integrity and performance capability. Accurate determination of engine condition will permit detection of incipient engine failures, repair or replacement of faulty components at the field level, increased time-between-overhaul, decreased aircraft losses, and a minimum of aborted missions.

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APPENDIX A1 (Continued)

The Navy has funded various mechanical condition analyzers since 1962. Both sonic and vibration techniques were studied. The best confidence levels were obtained utilizing piezo-electric accelerometers close-coupled to the part to be analyzed and utilizing various digital techniques to increase the signal to noise ratio and identify discriminants. Under work performed on a ground-based analyzer, a contract (reference (1)) with GE, Binghamton was let in April 1970 . . . to develop a mechanical condition analyzer for the TF34 engine. Fifty defects were programmed in the area of gears, bearings and FOD. A confidence level of 75 percent is specified. In the airborne analyzer area, two engine performance monitoring system contracts are being monitored (reference (3) and (4)). These contracts, with Emerson Electric and Garrett AiResearch, specify the development of engine performance parameters which are repeatable under various flight conditions and which can be used for an indication of engine performance.

Hamilton Standard has also been awarded a contract by AIR-536 to develop an airborne engine condition monitoring system for the A-7E aircraft. This system will be capable of handling both the TF30 and TF41 powered versions of this aircraft.

b. Objectives: (1) Develop a system suitable for airborne use which is applicable to Naval aircraft and which will give an accurate indication of engine health both in the categories of mechanical health and performance capability. The system should eliminate the need for scheduled overhaul and, in its place, substitute a system of overhaul as required. (2) Write a specification for construction of the subject system as applicable to a specific Naval aircraft.

c. Approach:

1. Review work done by the airlines and the military services on airborne and ground-based analyzers. Potential data sources are: Trans World Airlines, Kansas City, Mo.; American Airlines, Tulsa, Okla.; Garrett Corporation, Los Angeles, Calif.; and Emerson Electric, St. Louis, Mo. Investigation should also be made into the Boeing 747 system, the Air Force F-12/SR-71 aircraft system, and the Lockheed C5A system.

2. Investigate the state of the art of small digital computers suitable for airborne use.

3. Decide on a suitable display system as well as suitable parameters and logic.

4. Develop specialized transducers for turbine blade dimensions, turbine blade temperatures, and oil contamination.

5. Review techniques developed for the Navy under references (2) and (3) and check against data obtained at NAPTC for suitability.

6. Expand the techniques developed by GE Binghamton (reference (1)) for diagnosing defective rotating parts to a system suitable for computer entry. A confidence level of at least 75 percent should be the goal.

7. Integrate results of items 1 through 6 into a system to give total engine health (both mechanical and aero/thermodynamic).

8. Supply flow charts for computer programming.

9. Test a breadboard system on an engine at NAPTC.

10. Write a specification for the pertinent details of a complete system as applicable to a specific Naval aircraft.

d. Progress: In late FY 1970, NAPTC began assisting the Emerson Electric Co. in their exploratory study to detect and interpret anomalies in jet engine performance under transient operating conditions. Conferences between Emerson and NAPTC representatives established an acceptable test program which would provide meaningful test data. NAPTC personnel monitored the technical progress of the study and assisted Emerson whenever necessary by suggesting alternate or better methods for fulfilling their objectives.

In FY 1971, NAPTC provided Emerson Electric with complete transient test data on the J57-P-420 and the TF30-P-408. Testing has been completed and the data has been reduced and analyzed. NAPTC will continue to monitor the progress of Emerson's efforts until their two-phase study is completed.

In FY 1971, NAPTC has also reviewed work done by General Electric, Hamilton Standard, Teledyne, Trans-Sonics, Pratt and Whitney, Grumman, Lear Siegler, Bissett-Berman, Howell, and several other companies. In addition, NAPTC has discussed with the Air Force the work they have done on the Lockheed C5A MADAR system and their work done in conjunction with Garrett AiResearch. Work done by the airlines has also been reviewed.

e. Plans and Milestones:

FY 1972

Continued state-of-the-art review of airborne engine condition monitoring. Complete development of specialized transducers for turbine blade dimensions, turbine blade temperatures, and ore contamination and begin procurement of such items.

Complete review of techniques developed for the Navy under references (2), (3), and (4) and check against data obtained at NAPTC for suitability.

Expand the techniques developed by GE Binghamton (reference (1)) for diagnosing defective rotating parts to a system suitable for computer entry.

Begin development of diagnostic techniques and logic by engine testing.

FY 1973

Integrate results of above work into a system to give total engine health (both mechanical and aero/thermodynamic).

Supply flow charts for computer programming.

Test and evaluate selective computer and display hardware while further investigating diagnostic techniques and logic.

Begin formulating a specification for the pertinent details of a complete system as applicable to a specific Naval aircraft.

f. References:

- (1) GE Contract N62269-70-C-0315 Engine Analyzer for the TF34.
- (2) Emerson Electric contract N00019-70-C-0467 for feasibility study in FY 1970.
- (3) Garrett AiResearch contract N00019-70-C-0461 for feasibility study in FY 1970.
- (4) Emerson Electric contract N00019-71-C-0338 for feasibility study in FY 1971.

g. Major Procurements/Contracts:

FY 1970:

1. Emerson Electric Contract N00019-70-C-0467 for feasibility study
2. Garrett AiResearch contract N00019-70-C-0461 for feasibility study

FY 1971:

1. Contract with Emerson Electric for Phase II Feasibility Study -
2. Contract with Garrett AiResearch for Phase II Feasibility Study

FY 1972:

1. Contract for development of an oil condition monitor capable of identifying PPM contamination of at least iron.
2. Purchase software routines compatible with the XDS 910 computer.
3. Purchase turbine blade temperature sensor.
4. Purchase turbine blade dimension sensor.
5. Contract for computer interface of the vibration analyzer.
6. Purchase suitable display system.

FY 1973

1. Contract for conversion of software into machine language.
2. Continue contract for oil condition monitor
3. Procure flight-weight data acquisition system, data processor, and display system.
4. Contract for display software routines.

APPENDIX A2
AIRTASK/WORK UNIT ASSIGNMENT
NAVAIR FORM 3930-1 (REV. 9-69)DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
WASHINGTON, D.C. 20380See NAVFIR 3900.8 or ~~NAVAIR 3900.8~~ for applicable details on completing this form.CLASSIFICATION
UNCLASSIFIED

12 July 1971

PAGE 1 OF 3

| | | |
|---|---------------------------|------------|
| COMMANDER | AIR TASK NO. | AMEND. NO. |
| Commanding Officer Naval Air Propulsion Test Center Trenton, New Jersey 08628 | A3305360/2183/2F00433301 | AMEND. NO. |
| NAVAIR PROJECT ENGINEER | WORK UNIT NO. | AMEND. NO. |
| K. H. Guttmann, X22519 | N. A. | |
| | EFFORT LEVEL | |
| | Normal | |
| | CLASSIFICATION OF AIRTASK | |
| | Unclassified | |

1. The AIRTASK ~~XXXXXXXXXXXXXX~~ described below is assigned in accordance with the indicated effort level and schedule. Planning authorization for AIRTASKS will be provided in separate correspondence. If this AIRTASK/~~XXXXXXXXXXXXXX~~ cannot be accomplished as assigned, advise the Commander, Naval Air Systems Command, and the NAVAIRSYSCOM T&F COORDINATOR, if applicable.

2. Cancellation, References and/or Enclosures:

- a. Cancellations: None.
- b. References:
 - (a) NAVMAT Instruction 3910.13 of 30 January 1968
 - (b) NAVFIR Instruction 3900.8 of 11 July 1969
 - (c) DD Form 1634 Research and Development Planning Summary Task Area Plan 32.433.301, Auxiliary Equipment, March 1971
 - (d) Work Unit Plan NAPTC-624, "Turbine Engine Diagnostics Development", 8 June 1971
 - (e) Work Unit Plan NAPTC-625, "Feasibility of Integral Engine Generator", 8 June 1971
 - (f) Work Unit Plan NAPTC-626, "Advanced Composite Materials Gearbox", 8 June 1971
 - (g) Work Unit Plan NAPTC-627, "Lightweight APU Development", 8 June 1971
 - (h) Work Unit Plan NAPTC-628, "High Altitude Ejector Fuel Pump", 8 June 1971
- c. Enclosures: None.
- 3. Technical Instructions:
 - a. Title: Auxiliary Equipment
 - b. Purpose: Assignment of effort under requirements for FY 72. Policies and guidelines in references (a) and (b) are applicable.
 - c. Background: Work performed previously under AIRTASK A3305360/2183/2F32433301.
 - d. Detailed Requirements: Execute the following work under this AIRTASK:
 - (1) Turbine Engine Diagnostics Development - See reference (d).
Initial estimated cost: **E. Lister, NAPTC, X391.** Cognizant Engineer:

| | |
|--|--------------------------|
| INITIALS (By Direction Cognizant Eng.) | DATE |
| D. H. WILLIAMS by direction | 6/25/1971 25 Jun 1971 |
| CLASSIFICATION AND CONTROL MARKING | |
| UNCLASSIFIED | |

~~UNCLASSIFIED~~

- (2) Feasibility of Integral Engine Generator - See reference (e).
Initial estimated cost: Cognizant Engineer:
J. J. Curry, NAPTC, X389.
- (3) Advanced Composite Materials Gearbox - See reference (f).
Cognizant Engineer: J. J. Curry, NAPTC, X389. Initial estimated cost:
- (4) Lightweight APU Development - See reference (g). Cognizant Engineer: J. J. Curry, NAPTC, X389. Initial estimated cost:
- (5) High Altitude Ejector Fuel Pump - See reference (h). Cognizant Engineer: J. J. Curry, NAPTC, X389. Initial estimated cost:

e. Detailed Program Plan: Not Required.

4. Schedule:

- a. AIRTASK starting date: 1 July 1971
- b. AIRTASK completion date: 30 June 1972
- c. Oral review of progress under AIRTASK: 15 December 1971

5. Reports and Documentation:

a. Reports:

(1) AIRTASK progress reports shall be submitted on a quarterly basis. Reports shall include progress on each work unit and shall conform with applicable requirements of reference (b). Major milestones in the program shall be identified and progress against these, and the status of each, shall be clearly described. A single report shall be issued covering all of the AIRTASKS for Exploratory Development (Category 6.2) effort.

(2) Final and/or special reports shall be submitted in accordance with the referenced Work Unit Plans. All formal reports shall meet the marking, release and distribution of NAVAIR Instruction 5511.3 of 2 February 1968 and NAVMAT Instruction 4000.17 of 9 June 1965. Distribution statements imposed on reports shall be in accordance with applicable Work Unit Plans.

(3) Distribution of quarterly, special and final reports: Distribution is to be in accordance with the distribution established for the Center plus two (2) copies to AIR-330 directly.

b. Project Plan:

(1) In preparation for investigations to be undertaken during the forthcoming and ensuing fiscal years submit Work Unit Plans prepared in accordance with enclosure (3) of NAVAIR Instruction 3900.8 by 1 November and 1 May of each year. A Work Unit Plan is required for each existing or proposed item of work planned under the AIRTASK. The original of each Work Unit Plan shall be submitted to AIR-330 with copies to AIR-536.

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c. Progress Illustrations:

(1) In order to assist the originating divisions in presenting current project status and defending budgetary requirements, "8 x 10" viewgraphs shall be submitted on 1 December illustrating work accomplished, in progress, or planned (one copy each to AIR-330 and AIR-536).

d. The cognizant NAVAIR engineer shall be notified, with copy to AIR-330, of any changes in the AIRTASK which significantly affect the rate of progress, scope of work, or cost of task assignment.

6. Contractual Authority:

a. Contractual work shall not exceed the funding levels indicated in the Work Unit Plans without NAVAIR concurrence. Additionally, the cognizant NAVAIR engineer and AIR-330, shall be notified if planned contractual effort will not be met.

b. For contracts with planned values greater than \$50,000, submit recommendations and selected contractor's proposal to AIR-330 for prior review and approval.

7. Source and Disposition of Equipments: Not Applicable.

Aircraft Requirements: Not Applicable.

9. Cost Estimates:

a. AIRTASK summary cost:

b. The initial estimate of work unit costs listed in paragraph 3.d. above supersedes those in the referenced Work Unit Plans if any differences exist.

10. Status of Applicable Funds: Funds will be provided by Work Request.

Copy to:

Addressee (15)

SHIPHABGRP Morgantown, W. Va. 26506

NAVAIRSYSCOM T&E Coordinator

APPENDIX B

CRT MESSAGES

PLA = 00.0
 N₁ = 0000.0
 N₂ = 0000.0

TRACKING TRANSIENT

Mode: START, IDLE, ACCEL, TAKE-OFF, DECEL, PART POWER, COAST DOWN

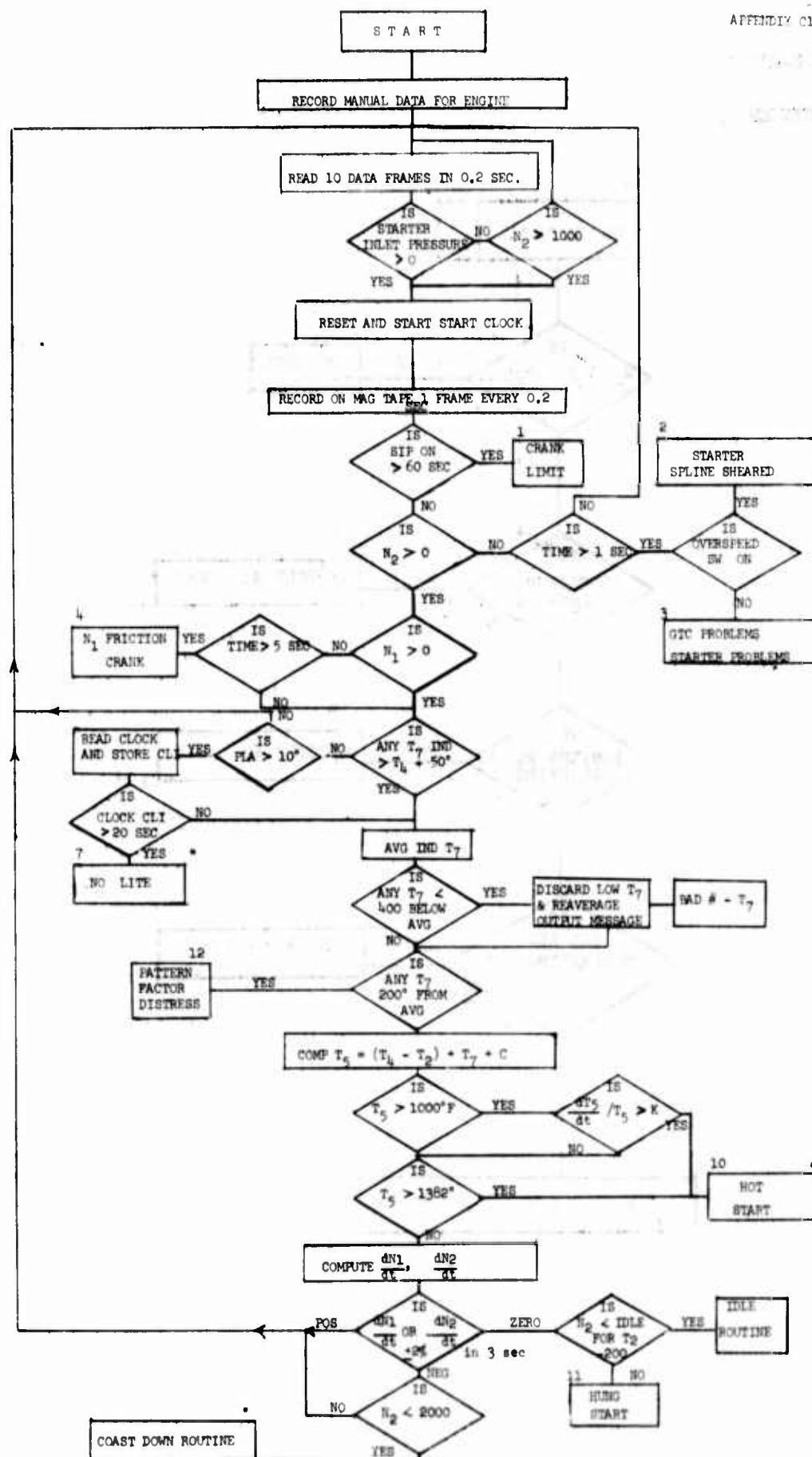
- 1 CRANK LIMIT¹
- 2 STARTER SPLINE SHEARED²
- 3 GTC PROBLEM²
- 4 N₁ FRICTION CRANK²
- 5 N₁ FRICTION COAST
- 6 N₂ FRICTION COAST
- 7 NO LITE
 - a. NO FUEL²
 - b. IGN #1 MALFUNCTION²
 - c. IGN #2 MALFUNCTION²
 - d. IGN SW OFF²
- 8 BAD TC¹
- 9 HOT SECTION DISTRESS³
- 10 HOT START²
 - a. STARTER DEFICIENT
 - b. GTC DEFICIENT
 - c. BLEEDS CLOSED
 - d. FUEL CONTROL DEFICIENT
- 11 HUNG START¹
- 12 PATTERN FACTOR DISTRESS
 - a. 1 2 3 4 5 6¹
- 13 VIBS DEFECT¹
 - ITEMS 1-70
- 14 OIL PROBLEM
 - a. DIRTY OIL³
 - b. METAL IN OIL³
 - c. FERROUS METAL

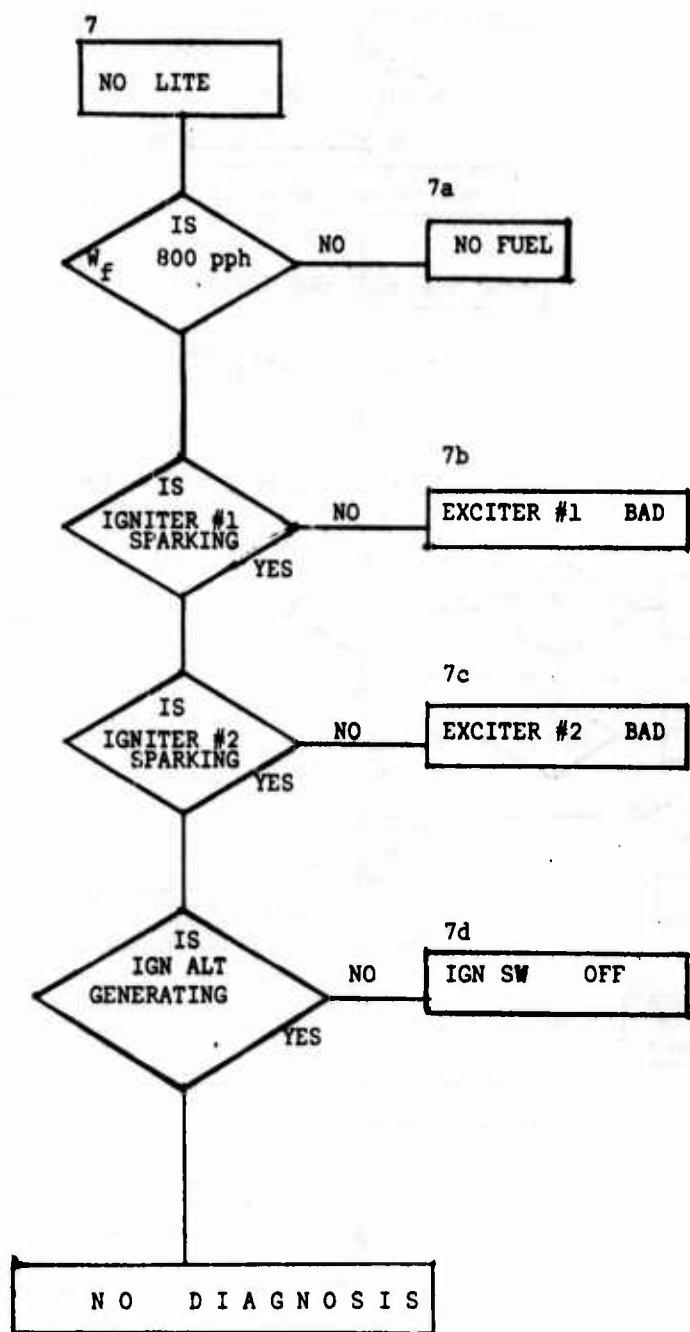
Demonstrated by:

1 = Engine Limit
 2 = False Signal
 3 = Lowered Limit

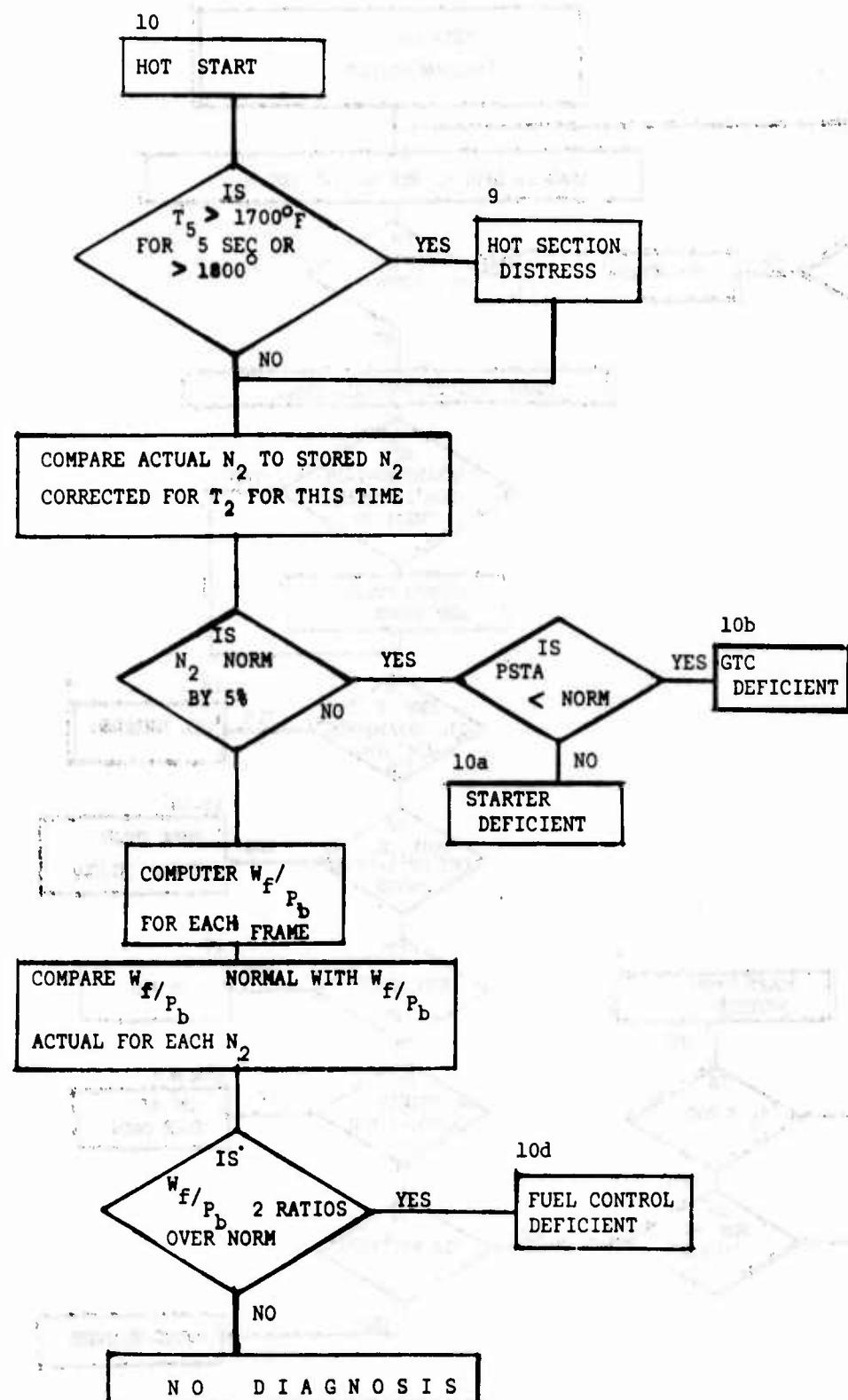
APPENDIX B (Continued)

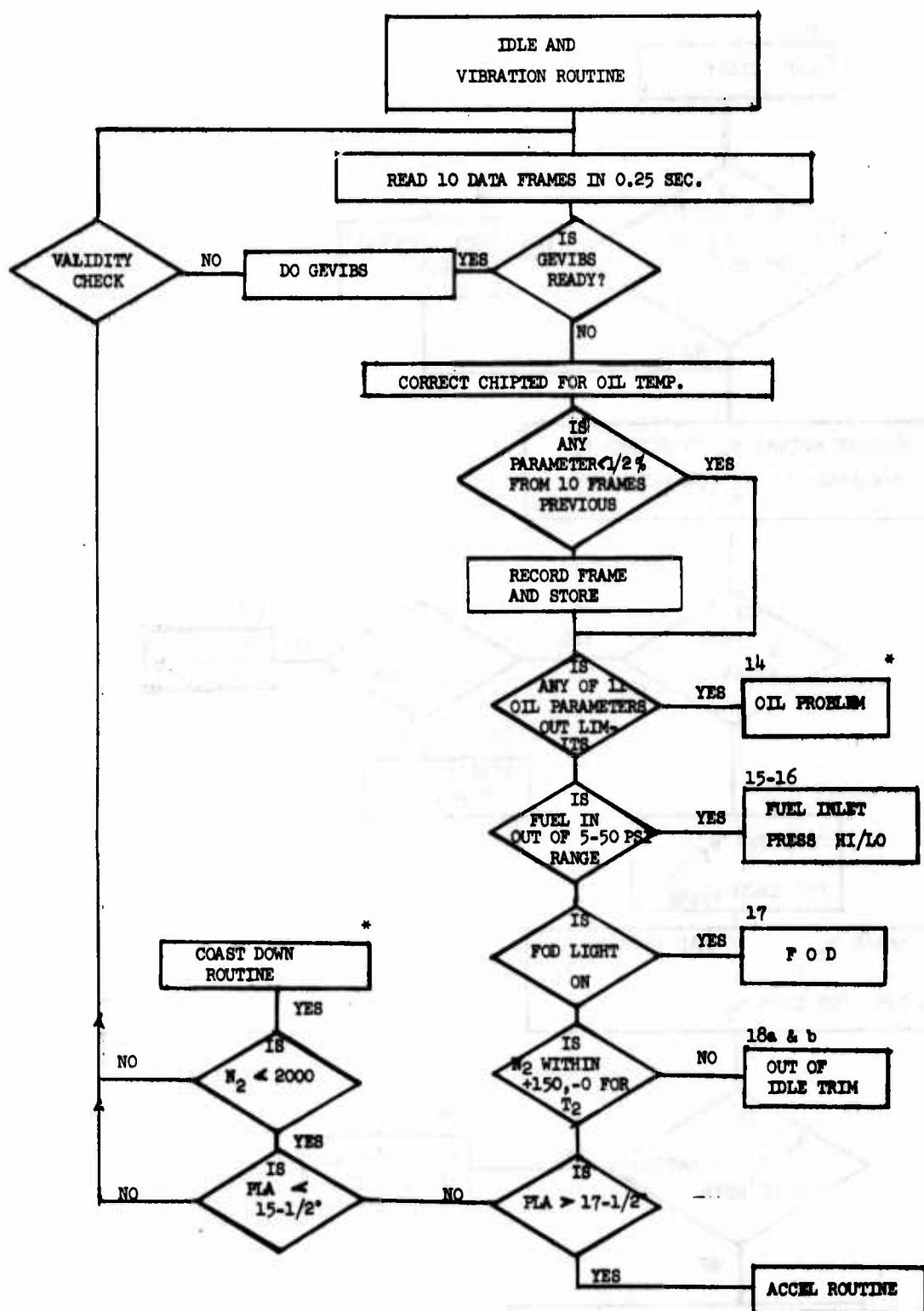
- d. NON FERROUS METAL
- e. OIL FLOW LO¹
- f. OIL FLOW HI³
- g. OIL USAGE HI
- h. BREATHER PRESS HI
- i. OIL PUMP BAD
- j. OIL PUMP BAD
- k. LO OIL PRESS³
- l. HI OIL TEMP
- 15. FUEL INLET PRESS HI¹
- 16. FUEL INLET PRESS LO¹
- 17. FOD²
- 18. a. HI IDLE TRIM¹
b. LO IDLE TRIM¹
- 19. FUEL ACCEL SCHED. DEFICIENT¹
- 20. BLEEDS CLOSE ACCEL HI¹
- 21. BLEEDS CLOSE ACCEL LO
- 22. BLEEDS OPEN DECEL HI
- 23. BLEEDS OPEN DECEL LO
- 24. BLEED VALVE HYSTERESIS
- 25. OUT OF TRIM¹
- 26. COOLING AIR FLOW DEFICIENT¹
- 27. FUEL DECEL SCHED. DEFICIENT¹
- 28. FLAME OUT
- 29. PERF DIAGNOSIS
 - a. N_1 PERF BAD
 - b. N_2 PERF BAD¹
 - c. P_{S3}/P_{T2} PERF BAD¹
 - d. P_{S4}/P_{T2} PERF BAD
 - e. T_5 PERF BAD
 - f. W_f PERF BAD
 - g. T_5 vs T_2 PERF BAD¹
 - h. N_2 vs T_2 PERF BAD¹
 - i. P_{S3}/P_{T2} vs $N_1/\sqrt{\theta} T_2$ ¹
- 30. END OF CYCLE

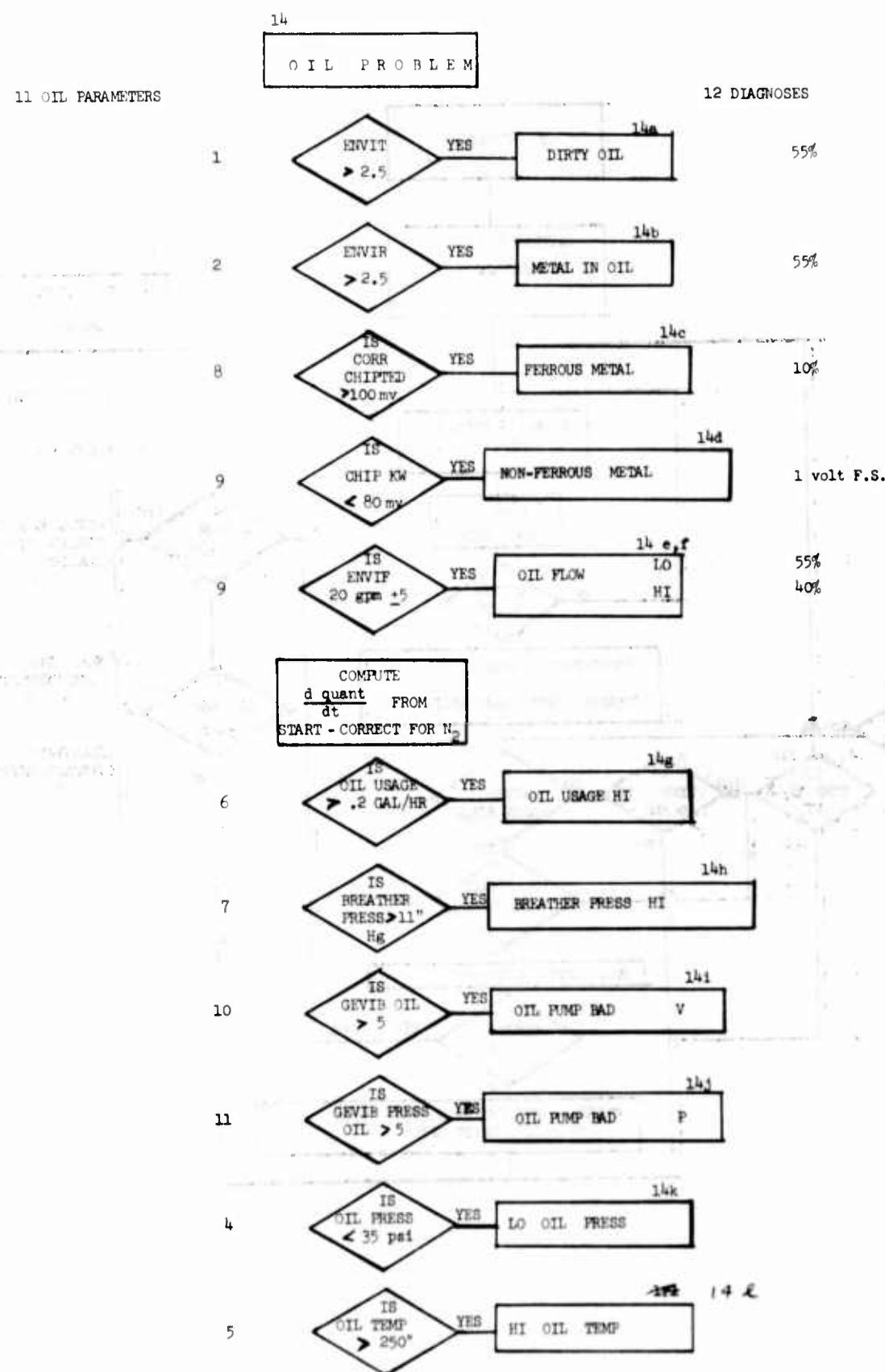




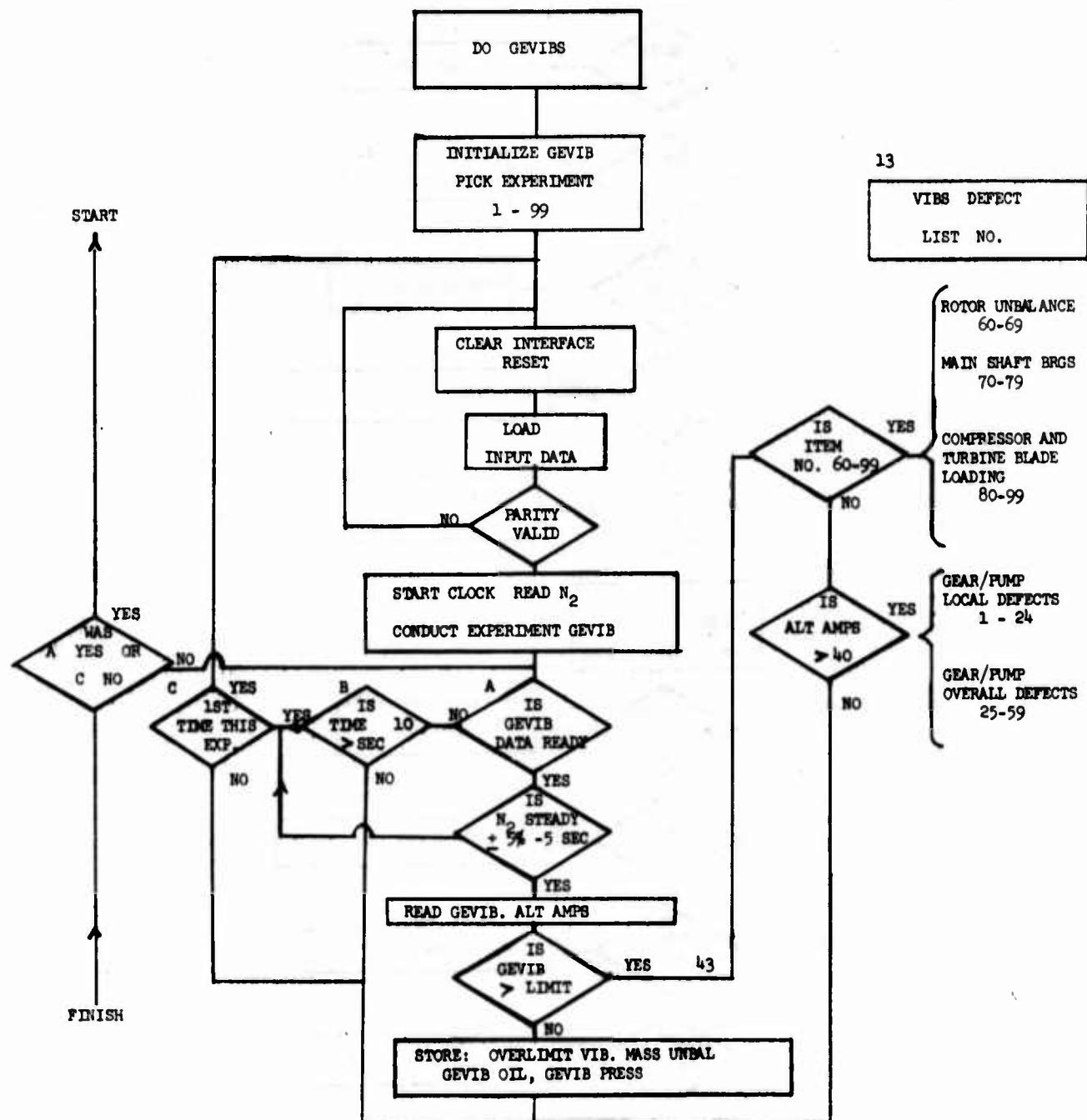
APPENDIX C3

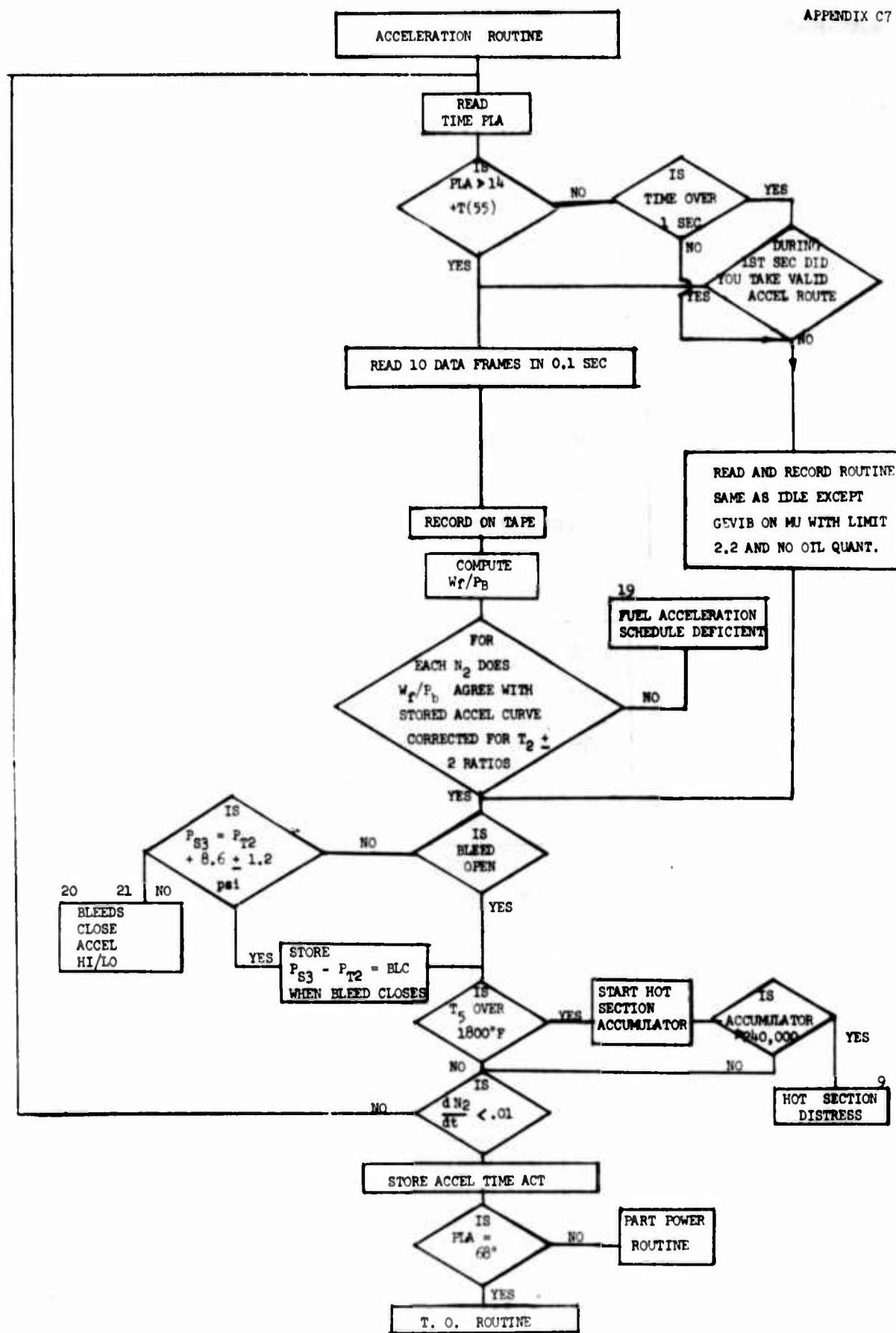




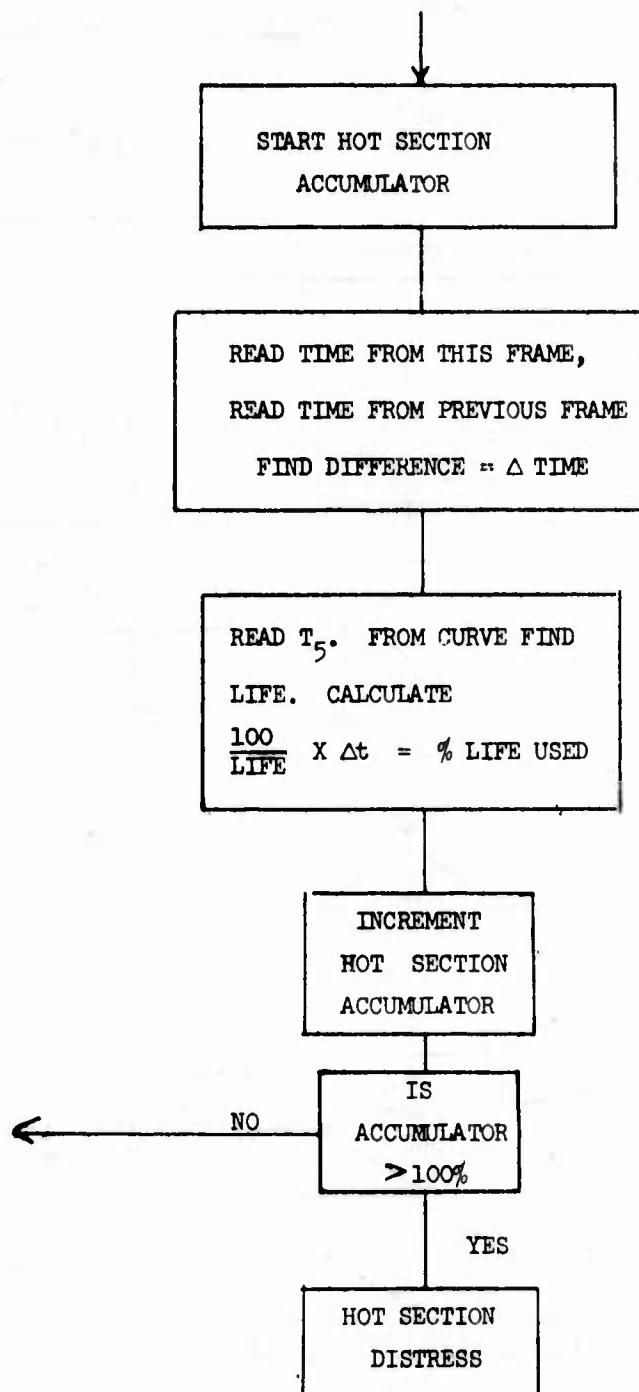


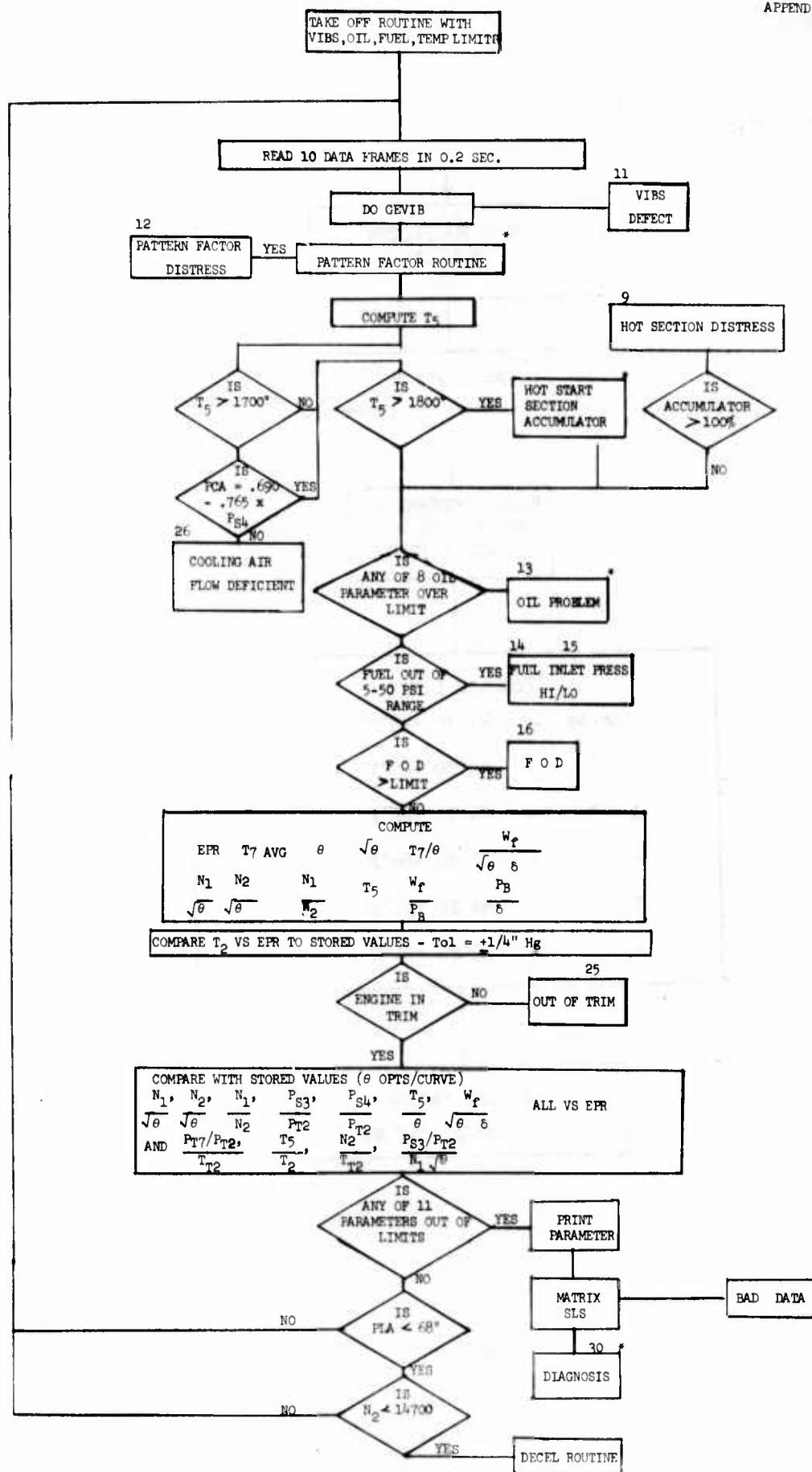
NO DIAGNOSIS



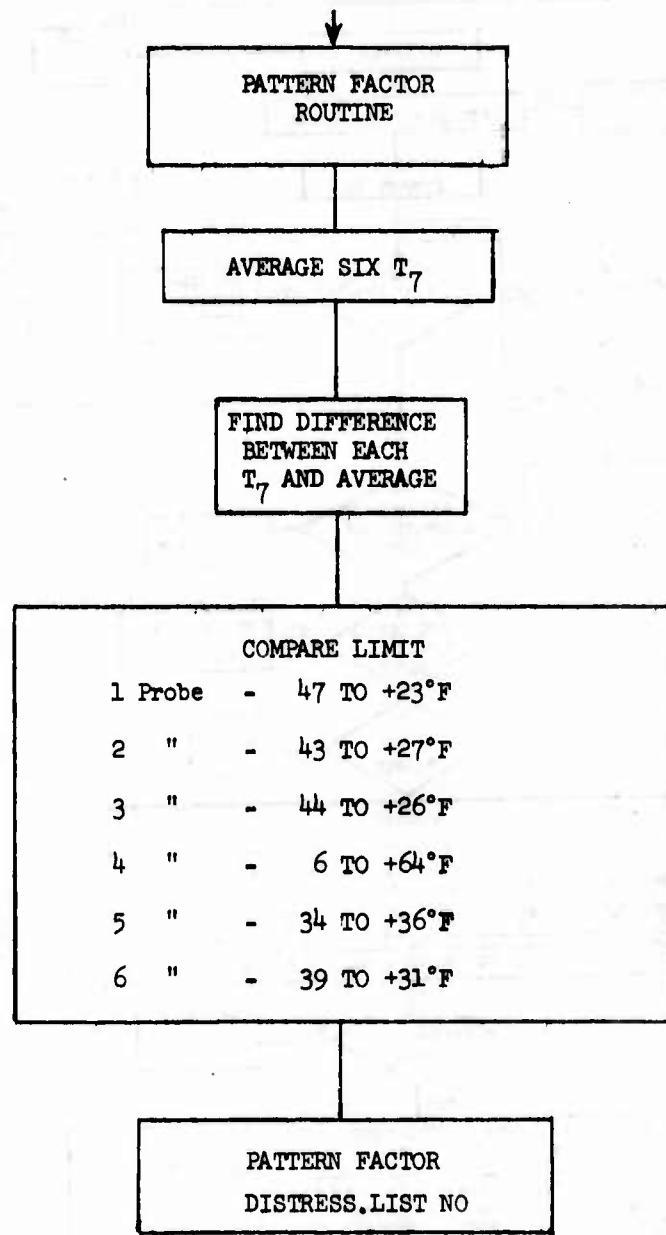


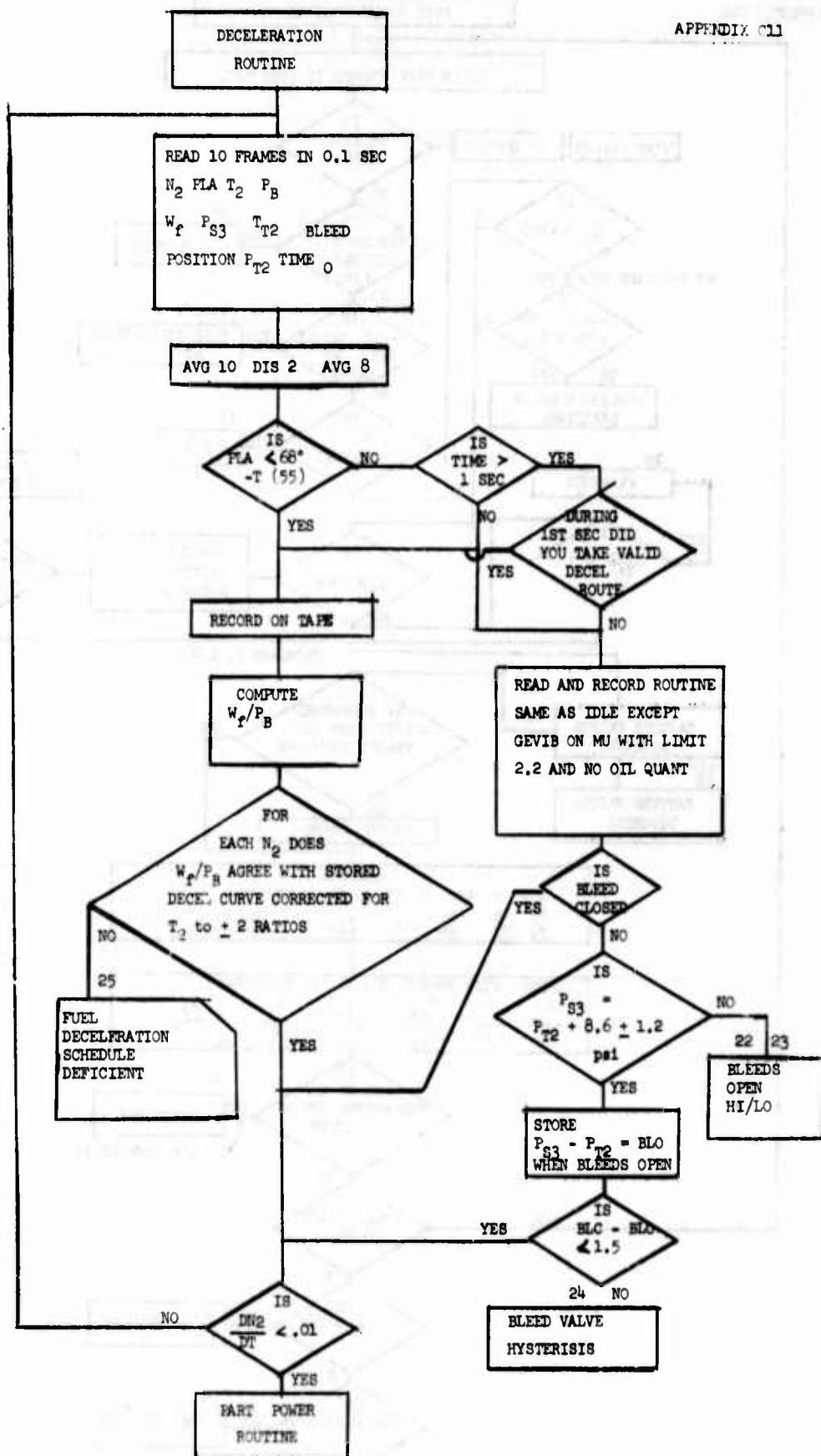
APPENDIX C8

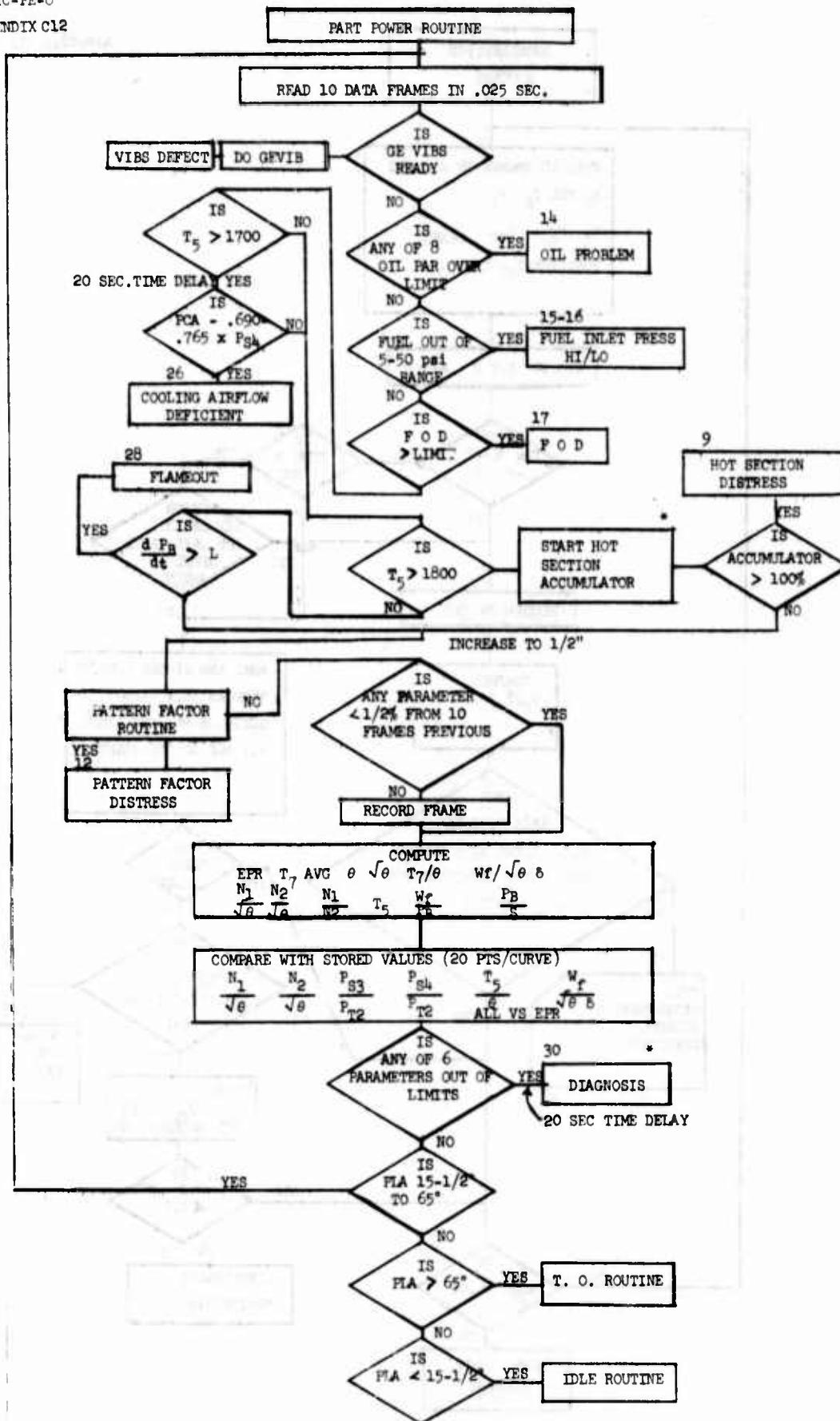


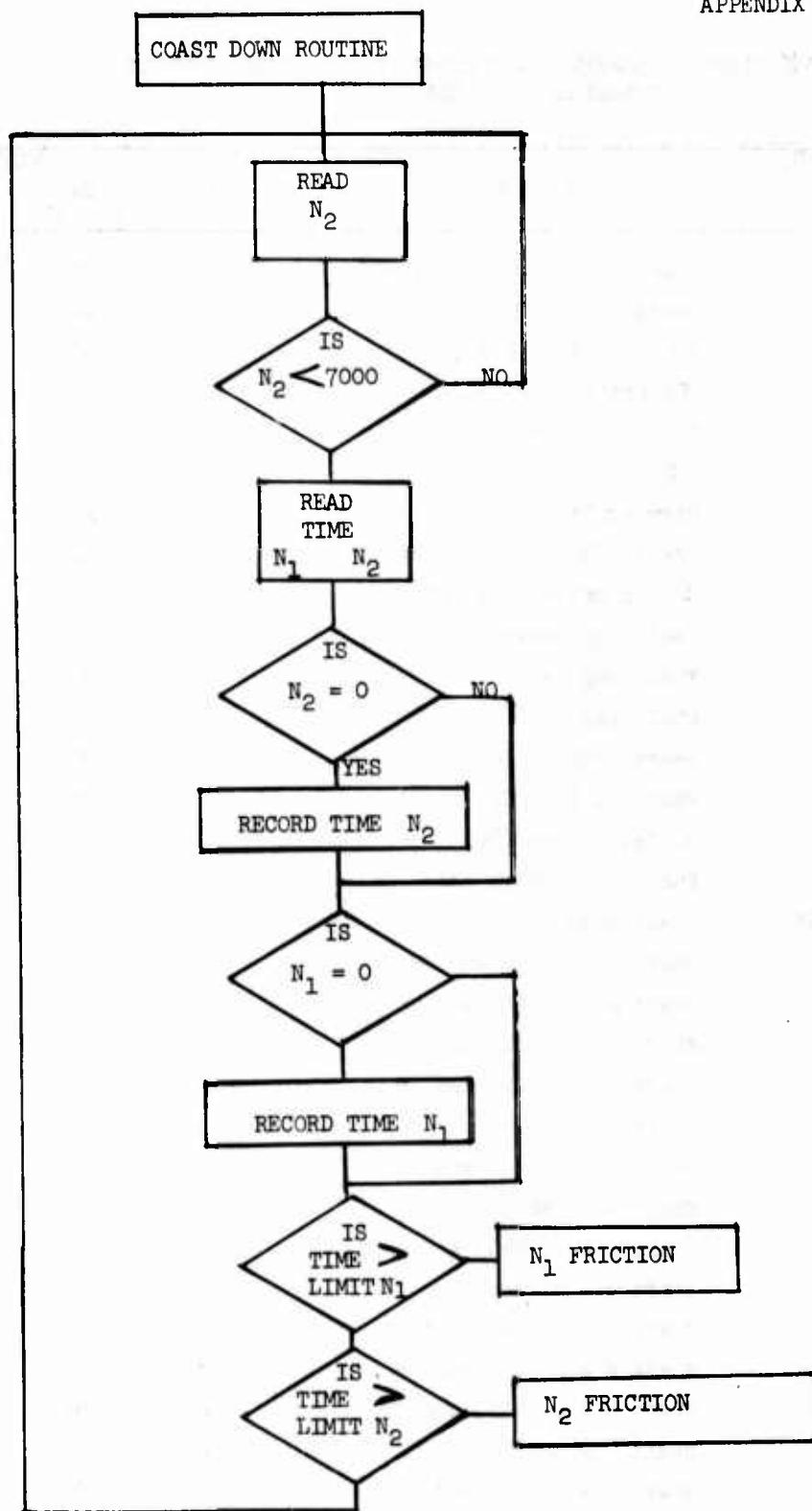


APPENDIX C10









APPENDIX D

EXPERIMENT CLASS: GEAR/PUMP/ACCESSORY DRIVE - LOCAL DEFECTS
FUNCTION SW - LOCAL

| EXPERIMENT NO. | COMPONENT | SENSOR NO. | READING | |
|-------------------|--------------------------------|---------------|-----------------|----------------------|
| | | | IDLE Run 819 | INTERMED. Run 820 |
| 1 | Tower Shaft Gears (9), (20) | 1 | 20 | 100 |
| 2 | Gears (21), (22) | 1 | 12 | 20 |
| 3 | Gears (27A), (27B), (35) | 1 | 17 | 19 |
| 4 | UHP Drive Gear (37) | 1 | 23 | 21 |
| 5 | CSD Drive Gear (23) | 2 | 14 | 22 |
| 6 | CSD 35 Tooth | 2 | 20 | 20 |
| 7 | Starter Drive (28) | 1 | 14 | 22 |
| 8 | Gears (24A), (24B), (24C) | 2 | 11 | 21 |
| 9 | De-air Drive Gear (25) | 2 | 15 | 17 |
| 10 | Fuel Pump Drive (29) | 1 | 20 | 21 |
| 11 | Fuel Pump (41) | 1 | 26 | 23 |
| 12 | Fuel Pump (42) | 1 | 23 | 21 |
| 13 | Gears (30A), (30B) | 1 | 20 | 20 |
| 14 | Main Oil Pump Drive (31) | 1 | 23 | 24 |
| 15 | N ₂ Tach Drive (32) | 1 | 22 | 21 |
| 16 | Fuel Boost Drive (26) | 2 | 20 | 21 |
| 17-24 | Unassigned | | | |
| 25 | Shaft A - G (9) and SB | 1 | 100 | 100 |
| 26 | Shaft A - G (20) and SB | 1 | 100 | 100 |
| 27 | Shaft B - G (21) and SB | 1 | 100 | 100 |
| 28 | Shaft B - G (22) and SB | 1 | 63 | 100 |
| 29 | Shaft C - G (23) and SB | 2 | 100 | 100 |
| 30 | Shaft C - CSD 37 and SB | 2 | 97 | 100 |
| 31 | Shaft W - CSD 35 | 2 | 62 | 98 |
| 32 | Shaft D - G (24A) and SB | 2 | 100 | 100 |
| 33 | Shaft D - G (24B) | 2 | 22 | 62 |
| 34 | Shaft D - G (24C) and SB | 2 | 100 | 100 |
| 35 | Shaft E - G (25) and SB | 2 | 100 | 100 |
| 36 | Shaft G - G (27A) and SB | 1 | 20 | 27 |
| 37 | Shaft H - G (27B) | 1 | 83 | 37 |
| 38 | Shaft H - G (35) and SB | 1 | 100 | 83 |

APPENDIX D (Cont'd)

| EXPERIMENT NO. | COMPONENT | SENSOR NO. | READING | |
|-------------------|------------------------------------|---------------|-----------------|----------------------|
| | | | IDLE Run 819 | INTERMED. Run 820 |
| 39 | Shaft J - G (37) and SB | 1 | 100 | 100 |
| 40 | Shaft J, K - UHP, LHP | 1 | 100 | 71 |
| 41 | Shaft L - G (28) and SB | 1 | 100 | 100 |
| 42 | Shaft M - G (29) and SB | 1 | 100 | 100 |
| 43 | Shaft M - FPG (38) | 1 | 100 | 100 |
| 44 | Shaft M ₁ - FPG (40) | 1 | 100 | 91 |
| 45 | Shaft P - FPG (41) | 1 | 100 | 97 |
| 46 | Shaft Q - FPG (42) | 1 | 100 | 100 |
| 47 | Shaft R - G (30A) | 1 | 49 | 43 |
| 48 | Shaft R - G (30B) | 1 | 31 | 64 |
| 49 | Shaft S - G (31) and SB | 1 | 92 | 100 |
| 50 | Shaft S, T - G (34A)G (34B) and SB | 1 | 100 | 100 |
| 51 | Shaft S, U - G (33A) G (33B) | 1 | 100 | 100 |
| 52 | Shaft V - G (32) and SB | 1 | 42 | 39 |
| 53 | Shaft F - G (26) and SB | 2 | 100 | 96 |
| 54-59 | Unassigned | | | |

EXPERIMENT CLASS: ROTOR MASS UNBALANCE - MILS TRACKING
FUNCTION SW - MASS UNB.

| | | | | |
|-------|------------------------------|---|---|----|
| 60 | Fan (V) | 3 | 5 | 21 |
| 61 | Fan (H) | 4 | 5 | 5 |
| 62 | Compressor (N ₁) | 5 | 6 | 57 |
| 63 | Turbine (N ₁) | 6 | 5 | 18 |
| 64 | Fan (V) (N ₂) | 3 | 2 | 19 |
| 65 | Fan (H) (N ₂) | 4 | 2 | 6 |
| 66 | Compressor (N ₂) | 5 | 2 | 48 |
| 67 | Turbine (N ₂) | 6 | 2 | 15 |
| 68-69 | Unassigned | | | |

EXPERIMENT CLASS: GEAR/PUMP/ACCESSORY DRIVE - LOCAL DEFECTS
FUNCTION SW - LOCAL

| | | | | |
|-------|---------------------|---|----|----|
| 70 | Main Oil Pump Drive | 7 | 19 | 21 |
| 71-79 | Unassigned | | | |

APPENDIX D (Cont'd)

EXPERIMENT CLASS: COMPRESSOR/TURBINE BLADE LOADING
FUNCTION SW - GROSS

| EXPERIMENT NO. | COMPONENT | SENSOR NO. | READING | |
|-------------------|----------------|---------------|-----------------|----------------------|
| | | | IDLE Run 819 | INTERMED. Run 820 |
| 80 | LPC - Stage 1 | 1 | 100 | 100 |
| 81 | 2 | | 100 | 100 |
| 82 | 3 | | 100 | 100 |
| 83 | 4 | | 100 | 100 |
| 84 | 5, 6 | | 100 | 100 |
| 85 | 7 | | 100 | 100 |
| 86 | 8 | | 100 | 100 |
| 87 | 9 | | 100 | 100 |
| 88 | HPC - Stage 10 | 6 | 100 | 100 |
| 89 | 11, 12, 13 | | 100 | 100 |
| 90 | 14, 15 | | 100 | 100 |
| 91 | 16 | | 68 | 100 |
| 92 | HPT - Stage 1 | 6 | 100 | 100 |
| 93 | LPT - Stage 2 | | 100 | 100 |
| 94 | 3 | | 100 | 100 |
| 95 | 4 | | 100 | 100 |

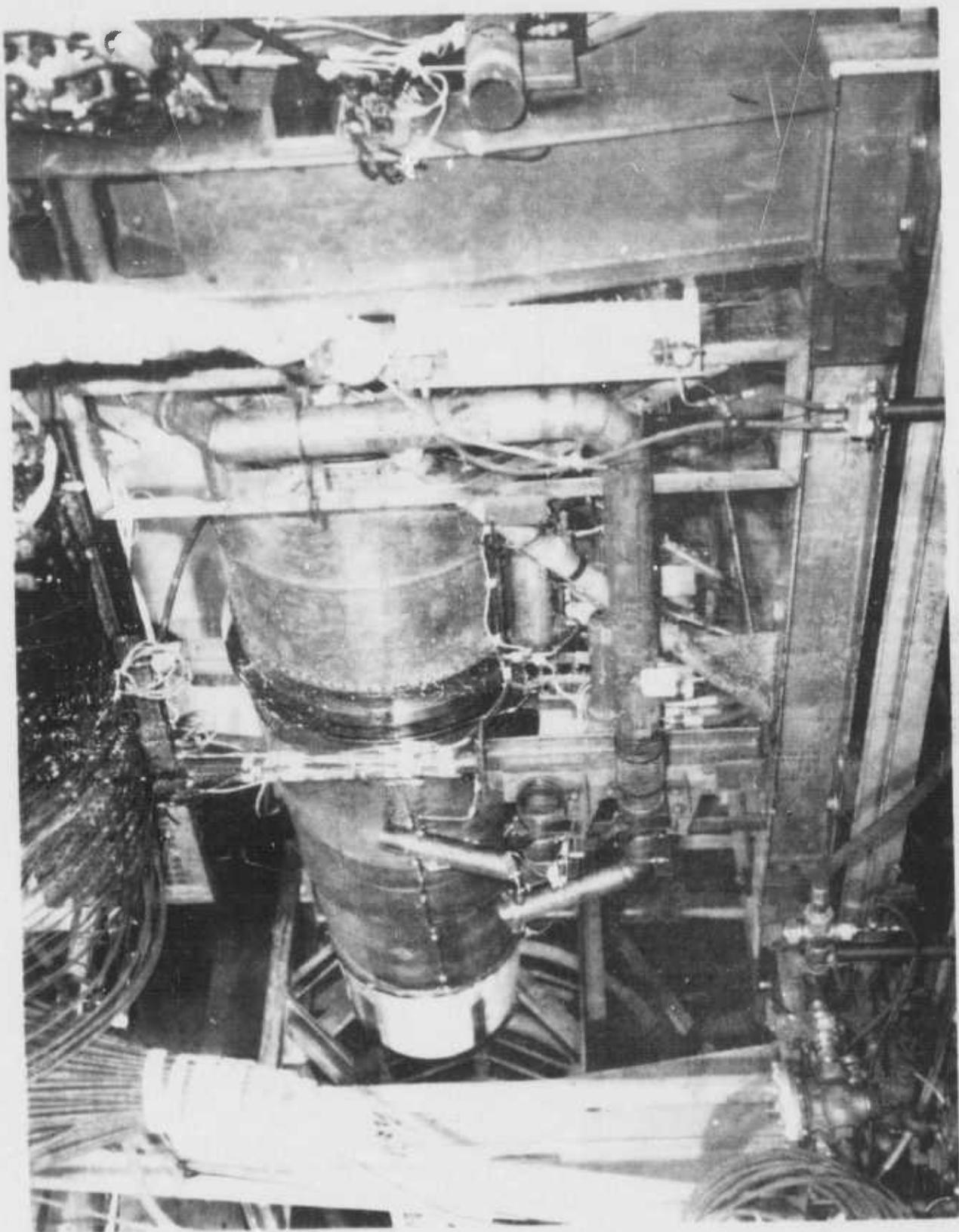
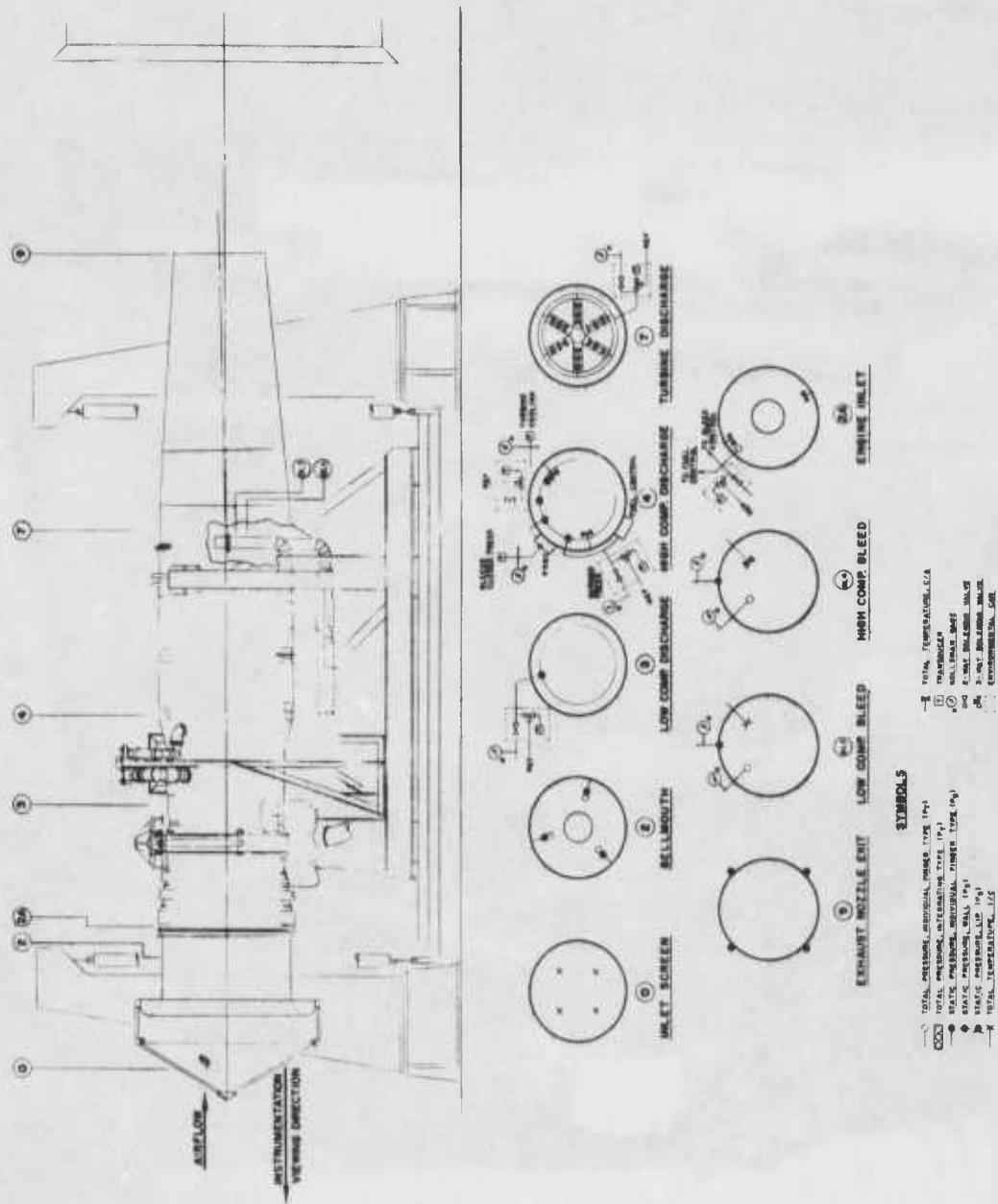


FIGURE 1: TF30-P-408 ENGINE INSTALLED IN 1W TEST CELL - RIGHT SIDE

Figure 2: TF30-P-408 TURBINE ENGINE DIAGNOSTICS
DEVELOPMENT TEST
ENGINE GAS PATH INSTRUMENTATION DIAGRAM



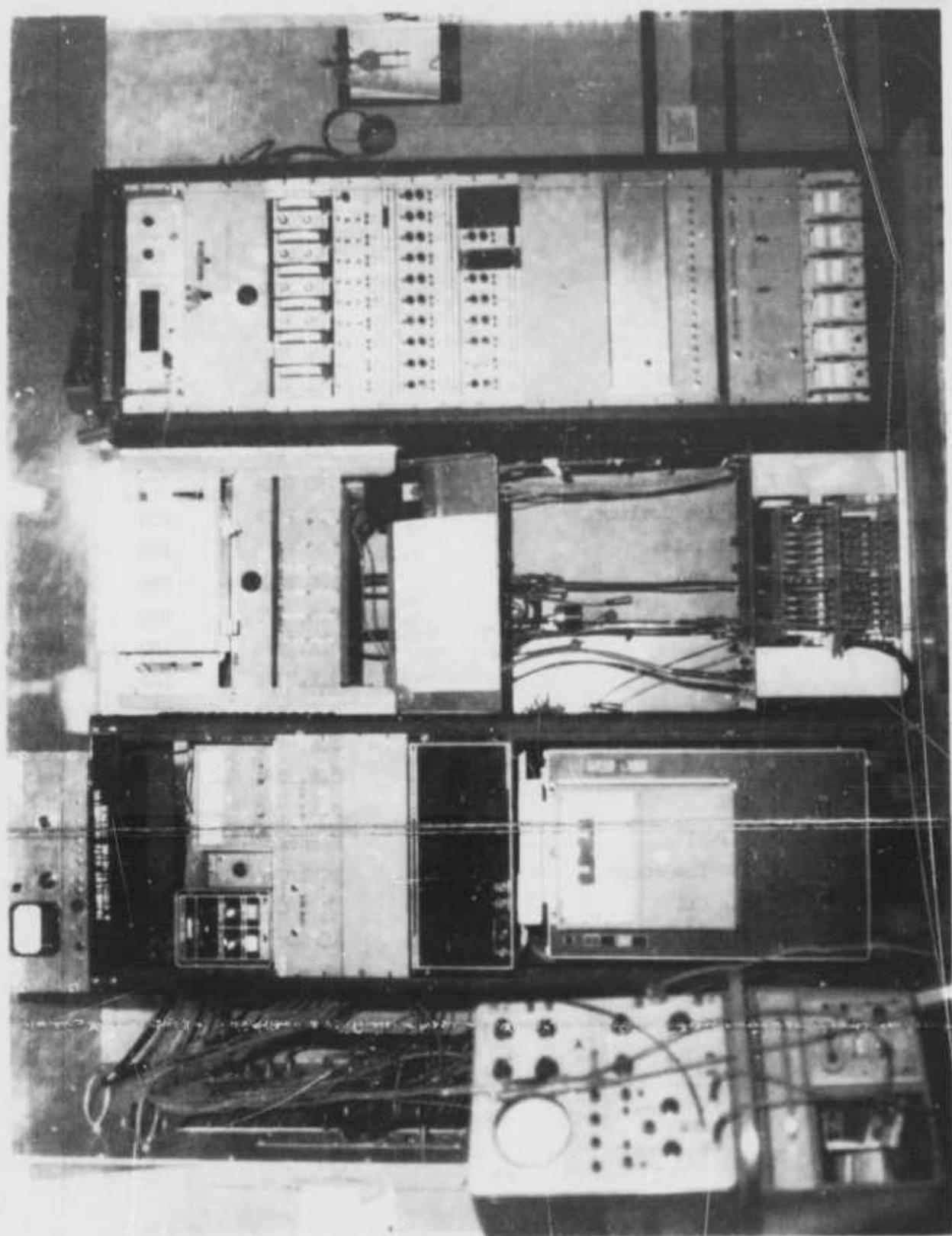


FIGURE 3: SIGNAL CONDITIONING

FIGURE 4: DATUM CHANNELS

| CHANNEL | PARAMETER | TRANSDUCER | GAIN |
|---------|---------------------|------------|------|
| 1 | T_0 | IC T/C | 500 |
| 2 | P_{T2} | 25 PSIA | 500 |
| 3 | P_{S3} | 100 PSIA | 250 |
| 4 | P_B | 300 PSIA | 250 |
| 5 | P_{S4} | 300 PSIA | 250 |
| 6 | P_{T7} | 50 PSIA | 250 |
| 7 | P Starter Air | 100 PSIA | 250 |
| 8 | 12th St. Bl. Pos. | 300 PSIA | 250 |
| 9 | P Oil Breather | 30 PSIA | 250 |
| 10 | P Turbine Cooling | 300 PSIA | 250 |
| 11 | P Fuel Inlet | 100 PSIA | 250 |
| 12 | P Main Oil | 100 PSIA | 250 |
| 13 | T_{T4} | C.A. T/C | 250 |
| 14 | $T_{T7} \#1$ | C.A. T/C | 100 |
| 15 | $T_{T7} \#2$ | C.A. T/C | 100 |
| 16 | $T_{T7} \#3$ | C.A. T/C | 100 |
| 17 | $T_{T7} \#4$ | C.A. T/C | 100 |
| 18 | $T_{T7} \#5$ | C.A. T/C | 100 |
| 19 | $T_{T7} \#6$ | C.A. T/C | 100 |
| 20 | T_{T5} (PWA) | Harness | 100 |
| 21 | T_f at Flowmeters | IC T/C | 500 |
| 22 | T Main Oil | IC T/C | 500 |
| 23 | N_1 Start | Airpax | 1 |
| 24 | N_2 Start | Airpax | 1 |

FIGURE 5: DATUM CHANNELS

| CHANNEL | PARAMETER | TRANSDUCER | GAIN |
|---------|--------------------------------|------------------|------|
| 25 | N_1 | Tach. | 1 |
| 26 | N_2 | Tach. | 1 |
| 27 | W_f | 3/4" FM | 1 |
| 28 | Oil Level | 1.5 PSIA | 250 |
| 29 | P.L.A. | Pos. Pot. | 1 |
| 30 | Oil Flow | Env. 1 | 1 |
| 31 | Oil Transmissivity | Env. 1 | 1 |
| 32 | Oil Reflectivity | Env. 1 | 1 |
| 33 | Gen. Phase Cur | Transf. | 5 |
| 34 | Starter Air Value | Switch | 1 |
| 35 | Short | | |
| 36 | Ignition #1 | Primary Tap | 50 |
| 37 | Ignition #2 | Primary Tap | 50 |
| 38 | T Oil Brgs. #1 | IC T/C | 500 |
| 39 | T Oil Brgs. #4, 4-1/2, 5 and 6 | IC T/C | 500 |
| 40 | Chip Detector | Tedeco | 1 |
| 41 | Oil Debris | K-WEST | 50 |
| 42 | FOD | GE | |
| 43 | Vibration | GE Analyzer | 1 |
| 44 | CSD Oil Press | 1000 PSIA | 250 |
| 45 | CSD Oil Temp | IC T/C | 500 |
| 46 | Thrust | 15K lb load cell | 500 |
| 47 | P_{S2} | 30 PSIA | 500 |
| 48 | Ignition Switch | Switch | |
| 49 | Ultrasonic Detector | | |
| 50 | Short | | |

FIGURE 6: ANALOG TAPE CHANNELS

| | | |
|----|--------------------------|----|
| 1 | Accelerometer | #1 |
| 2 | Accelerometer | #2 |
| 3 | Accelerometer | #3 |
| 4 | Accelerometer | #4 |
| 5 | Accelerometer | #5 |
| 6 | Accelerometer | #6 |
| 7 | Ultrasonic Microphone | |
| 8 | Oil Press Fluctuations | |
| 9 | Alternator Phase Current | |
| 10 | Thrust | |
| 11 | N_1 (Hz) | |
| 12 | N_2 (Hz) | |
| 13 | W_f (DC) | |
| 14 | Time Code Generator | |

FIGURE 7: CATHODE RAY TUBE PHOTOGRAPH



FIGURE 8: TEDD PROGRAM DESCRIPTION

PROGRAM FLOW

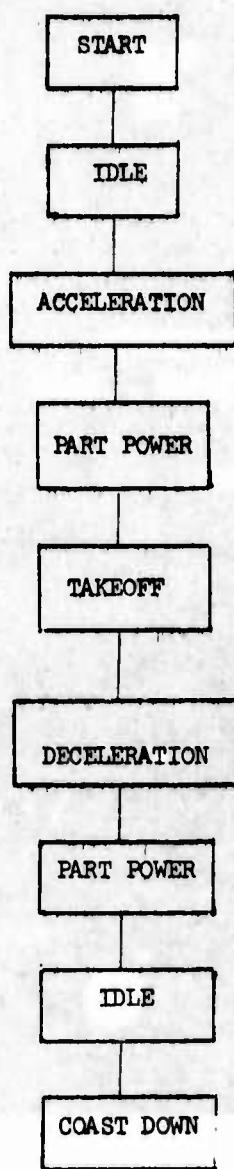
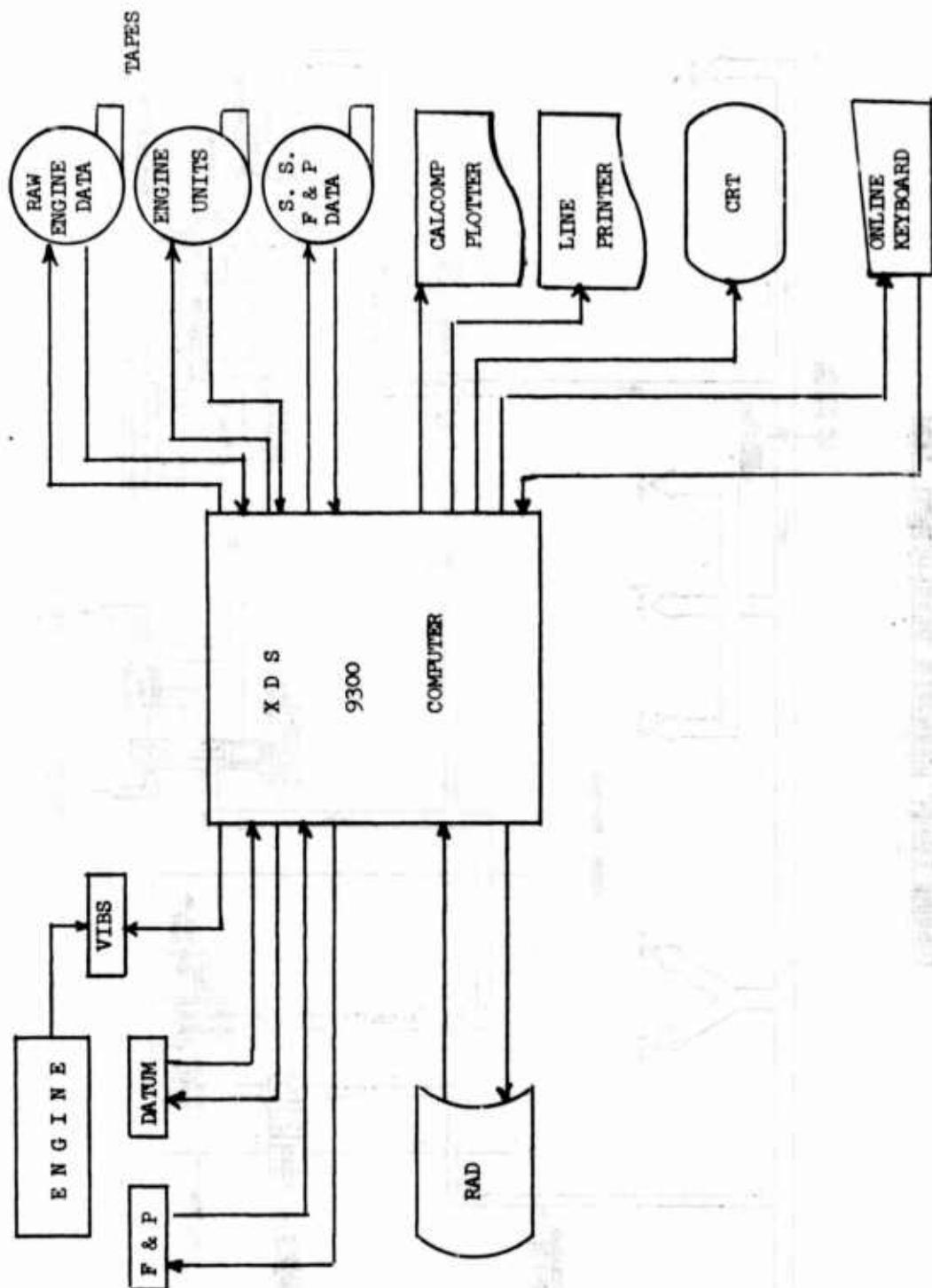


FIGURE 9: COMPUTER HARDWARE CONFIGURATION



**FIGURE 10: TF30-P-408 ENGINE LUBRICATION SYSTEM SCHEMATIC
TURBINE ENGINE DIAGNOSTIC DEVELOPMENT TEST**

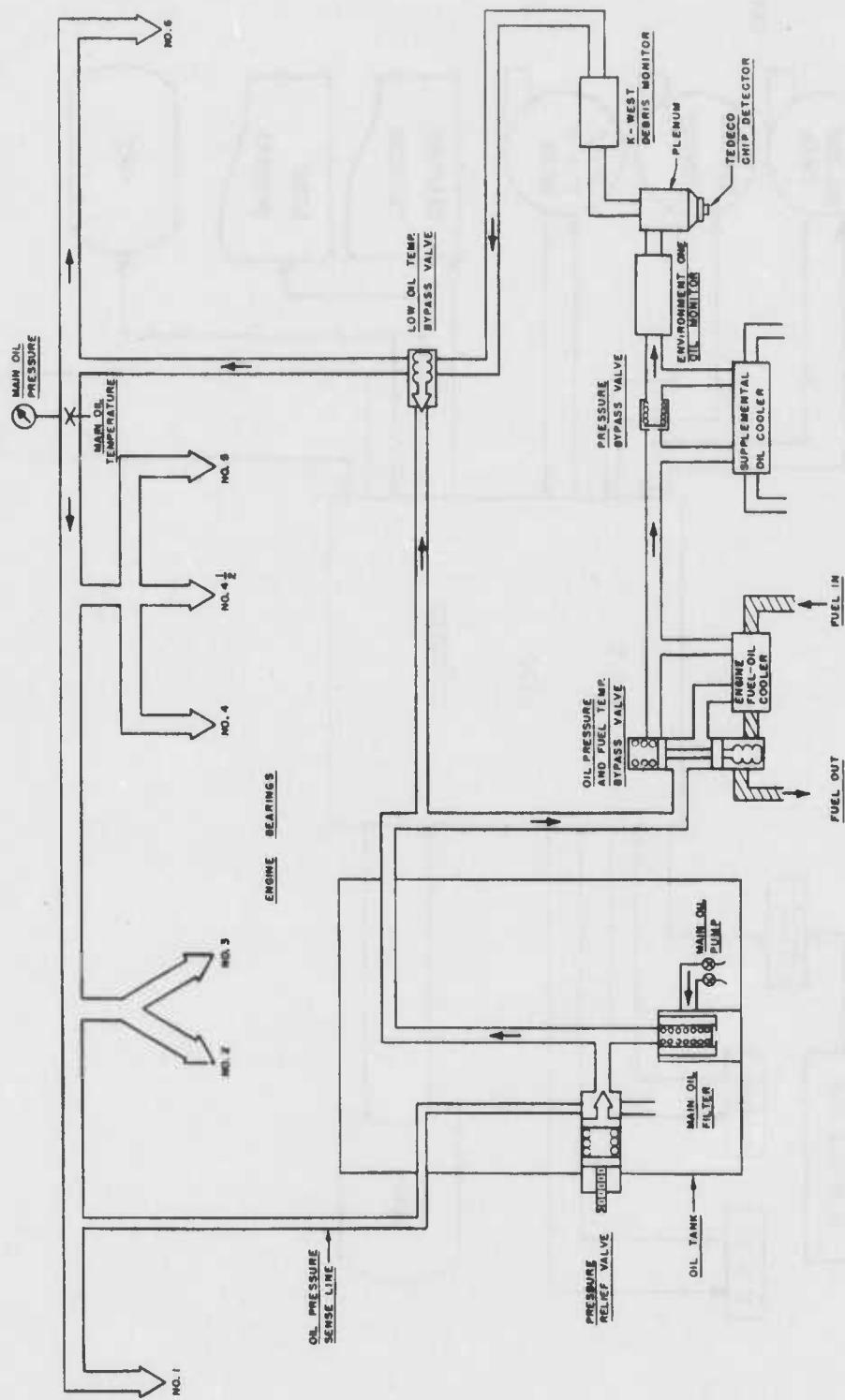


FIGURE 11: OIL SYSTEM ON ENGINE TRANSDUCERS

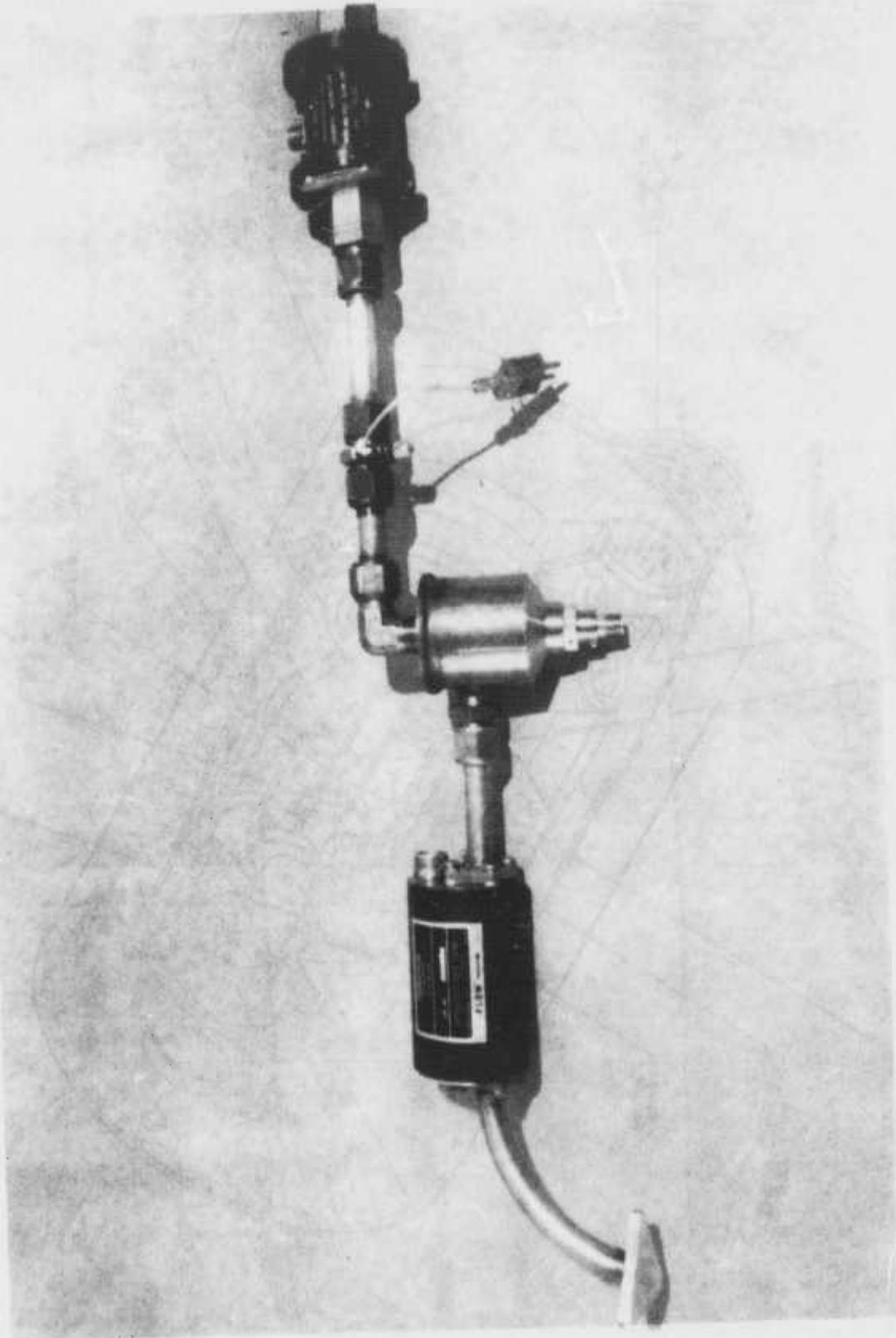
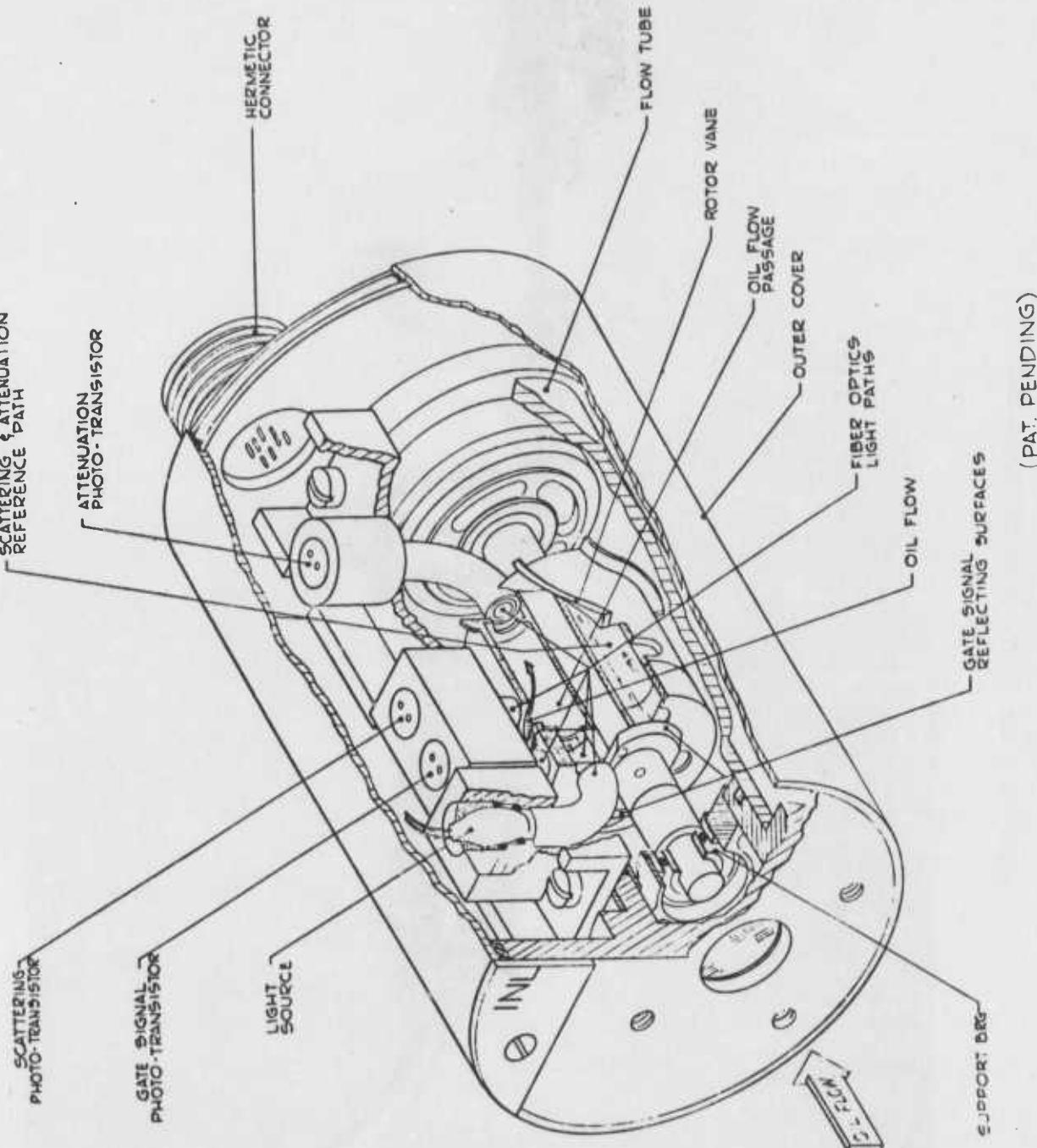


FIGURE 12: "ENVIRONMENT ONE" OIL MONITOR
SCATTERING & ATTENUATION
REFERENCE PATH



(PAT. PENDING)

FIGURE 13: TEDECO CHIP DETECTOR

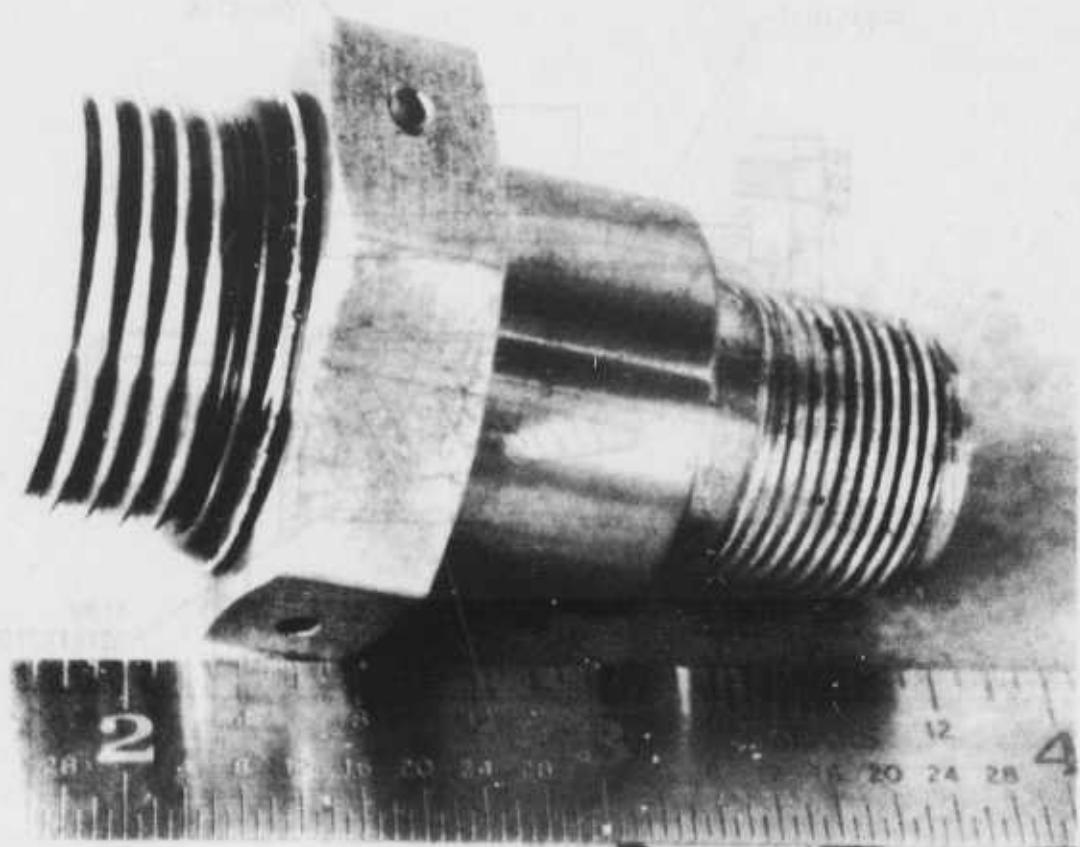


FIGURE 14: K-WEST DEBRIS MONITOR

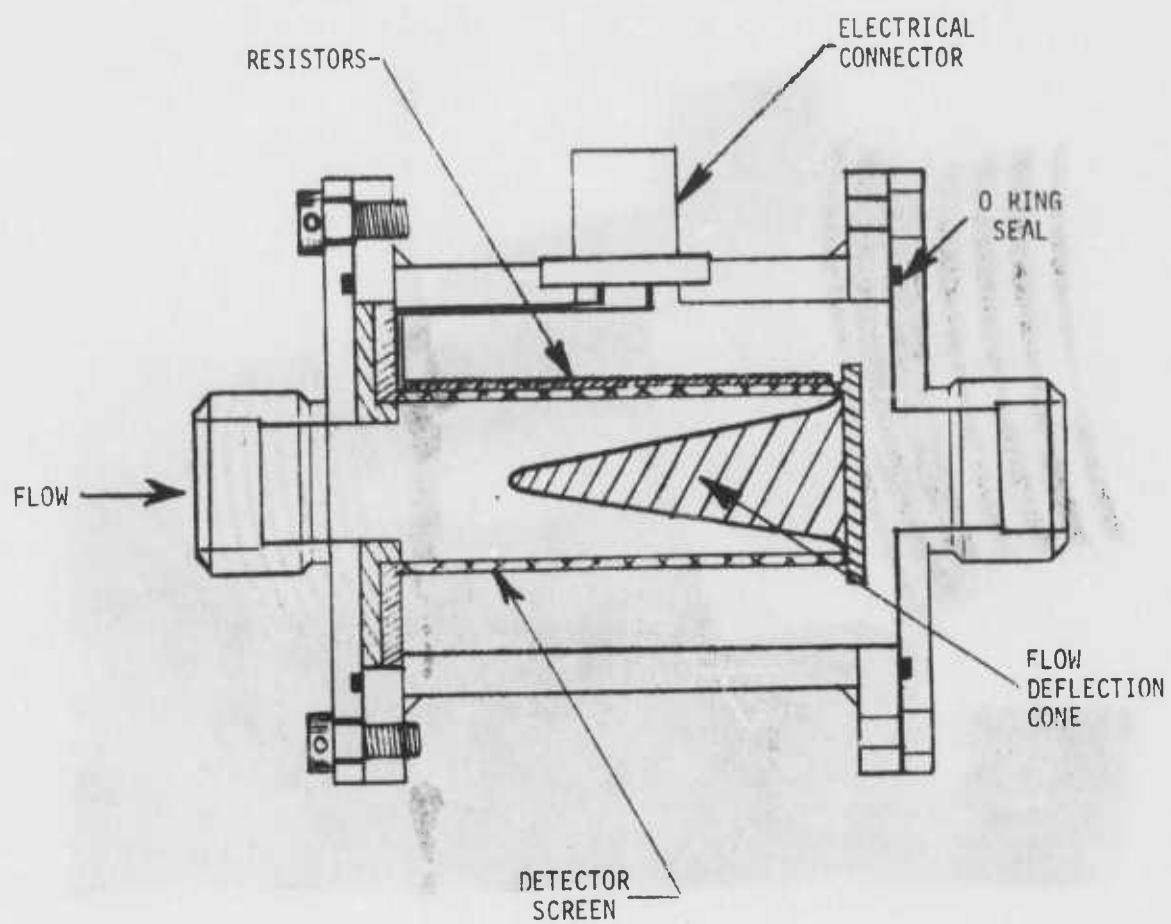


FIGURE 15: TACHOMETER

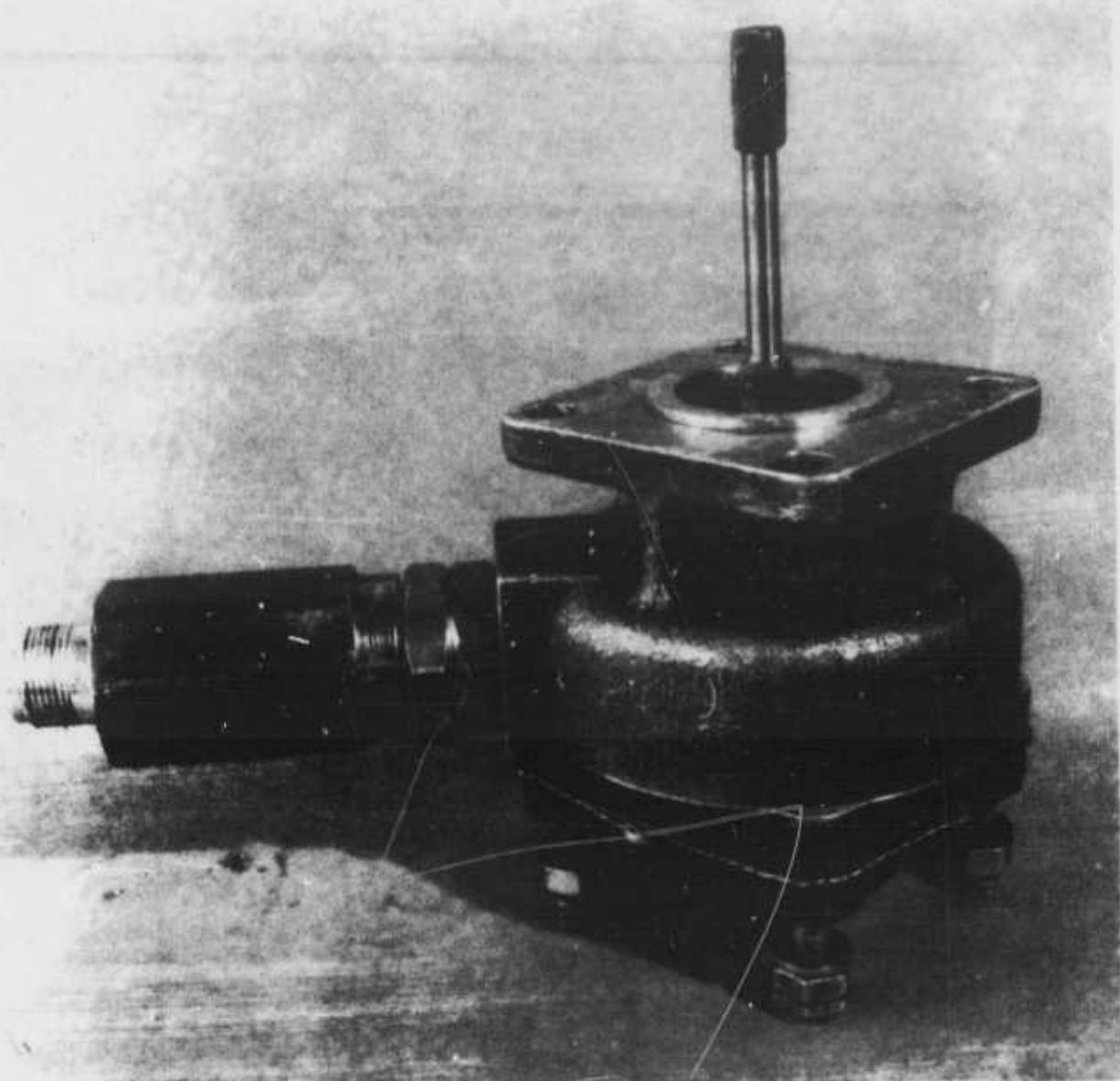


FIGURE 16: GENERAL ELECTRIC CO. VIBRATION SYSTEM

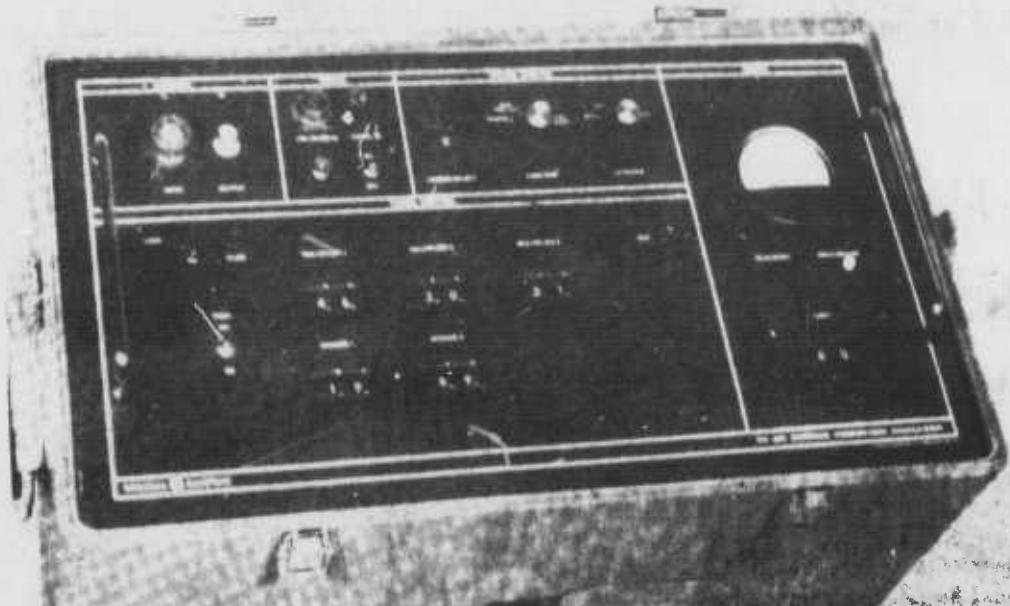


FIGURE 17: HOT SECTION LIFE VS TURBINE INLET TEMPERATURE

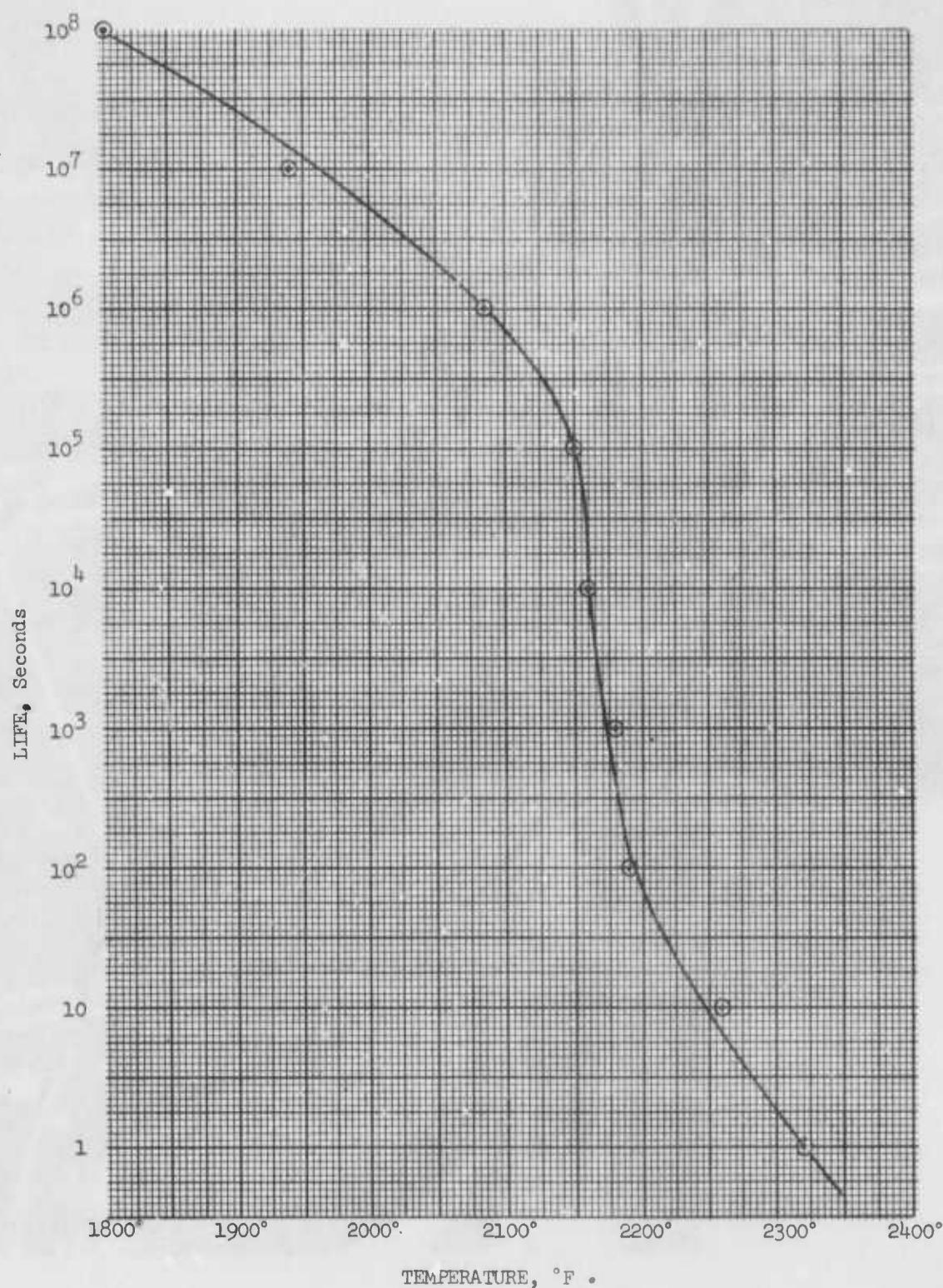


FIGURE 1A: ULTRASONIC MICROPHONE

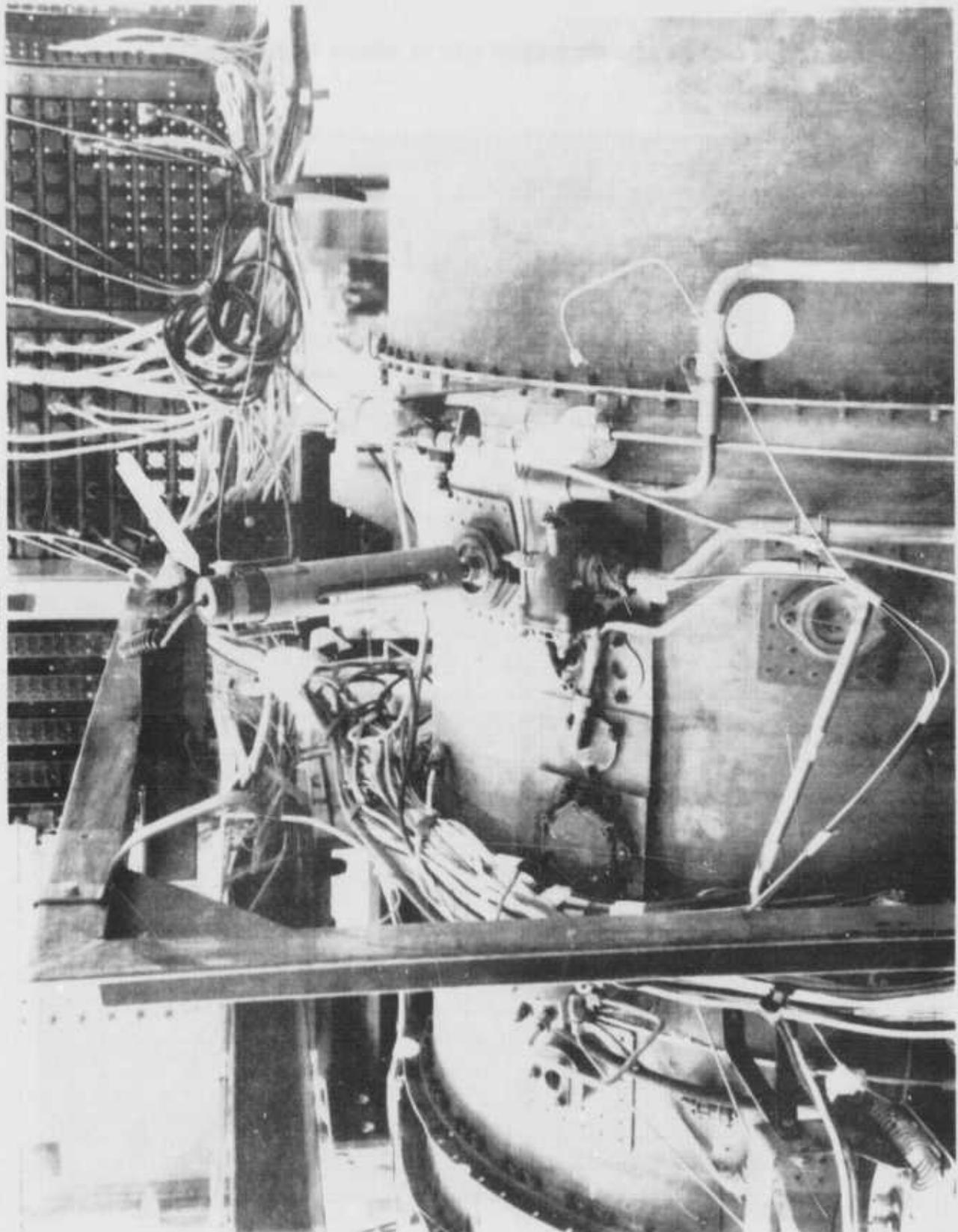


FIGURE 19: TF30-P-408 ENGINE PERFORMANCE LIMITS

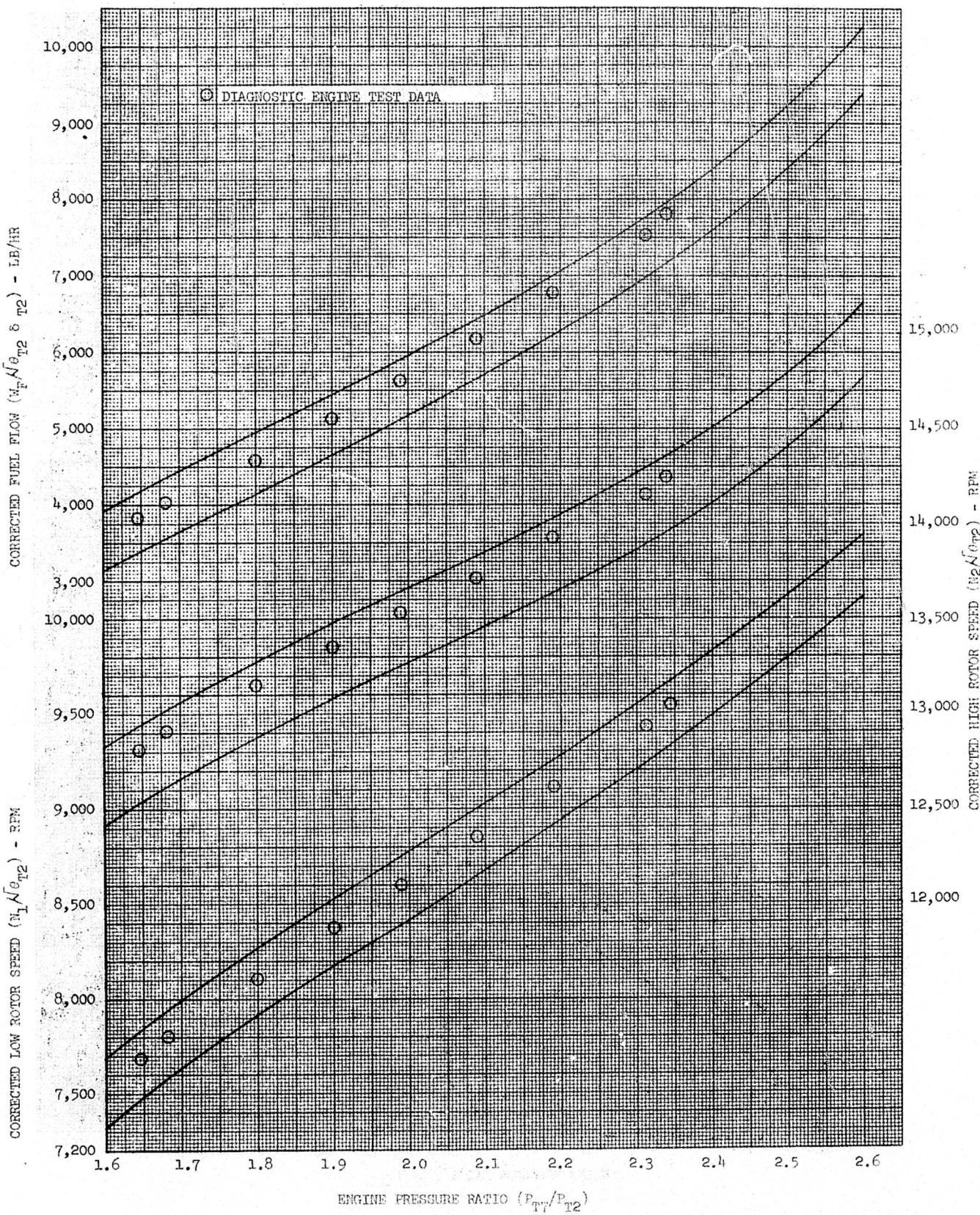


FIGURE 20: TF30-P-408 ENGINE PERFORMANCE LIMITS

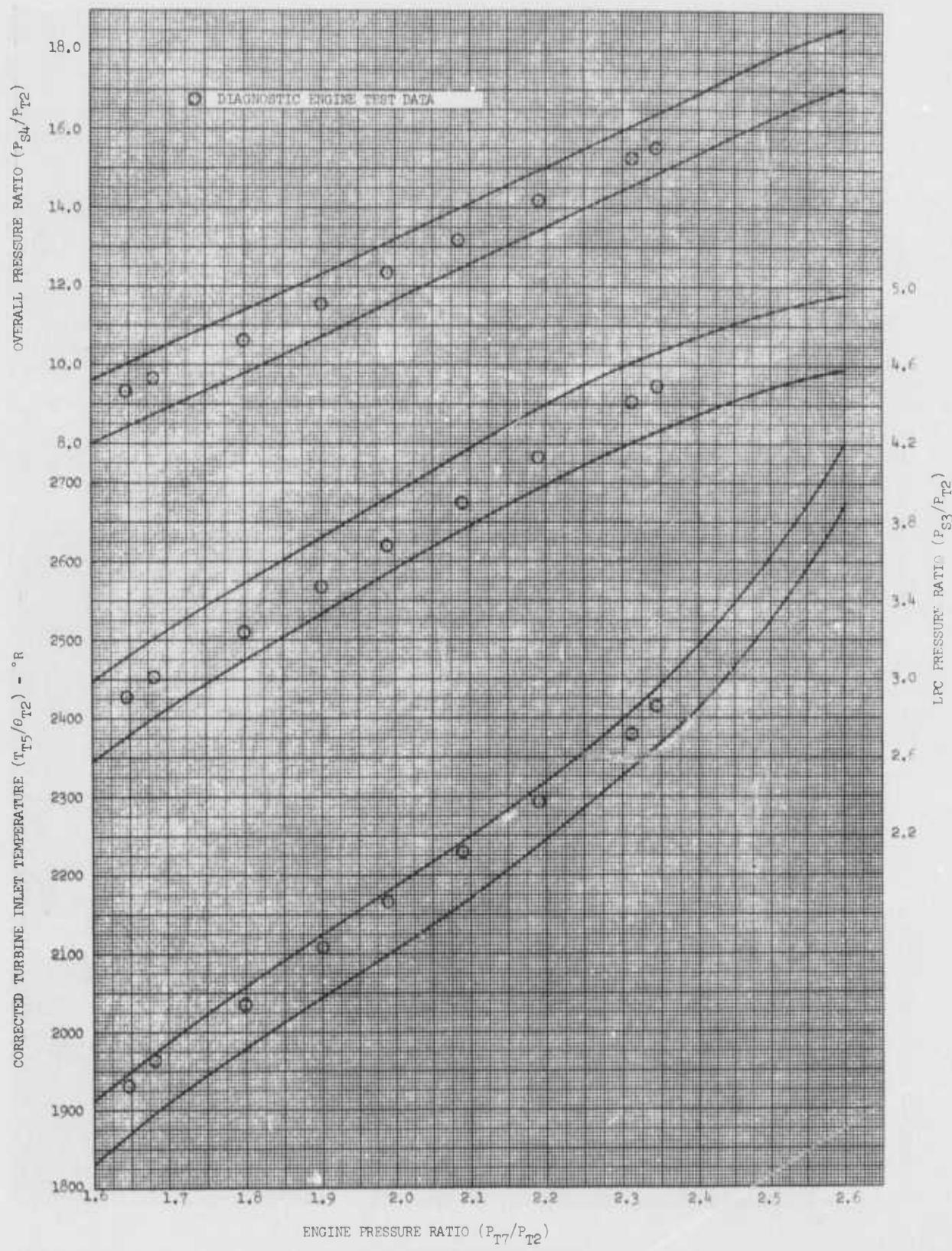
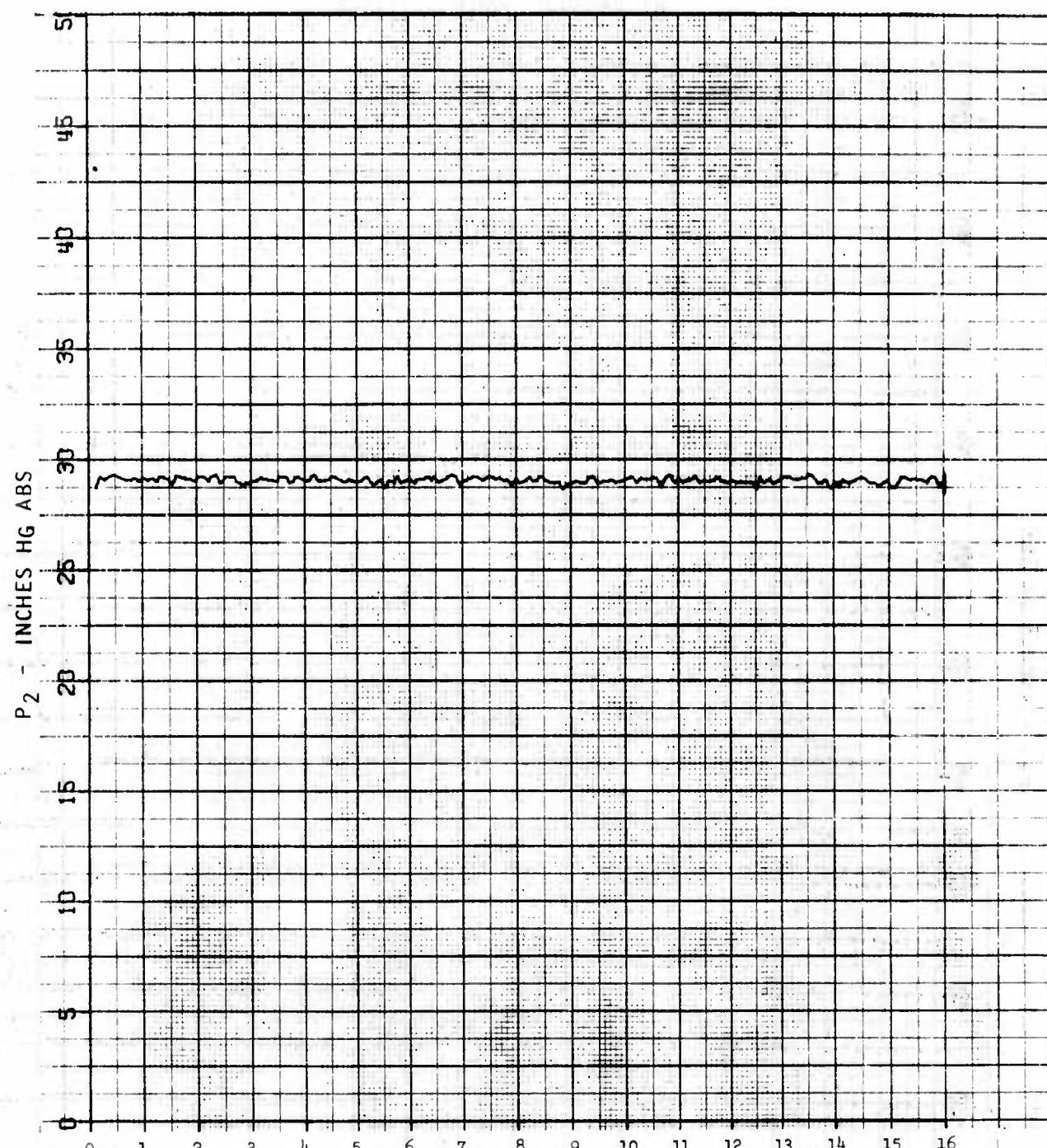


FIGURE 21: INLET TOTAL PRESSURE VS TIME
AT INTERMEDIATE POWER

ELAPSED TIME - SECONDS

FIGURE 22: TURBINE DISCHARGE PRESSURE VS TIME
AT VARIOUS POWER SETTINGS

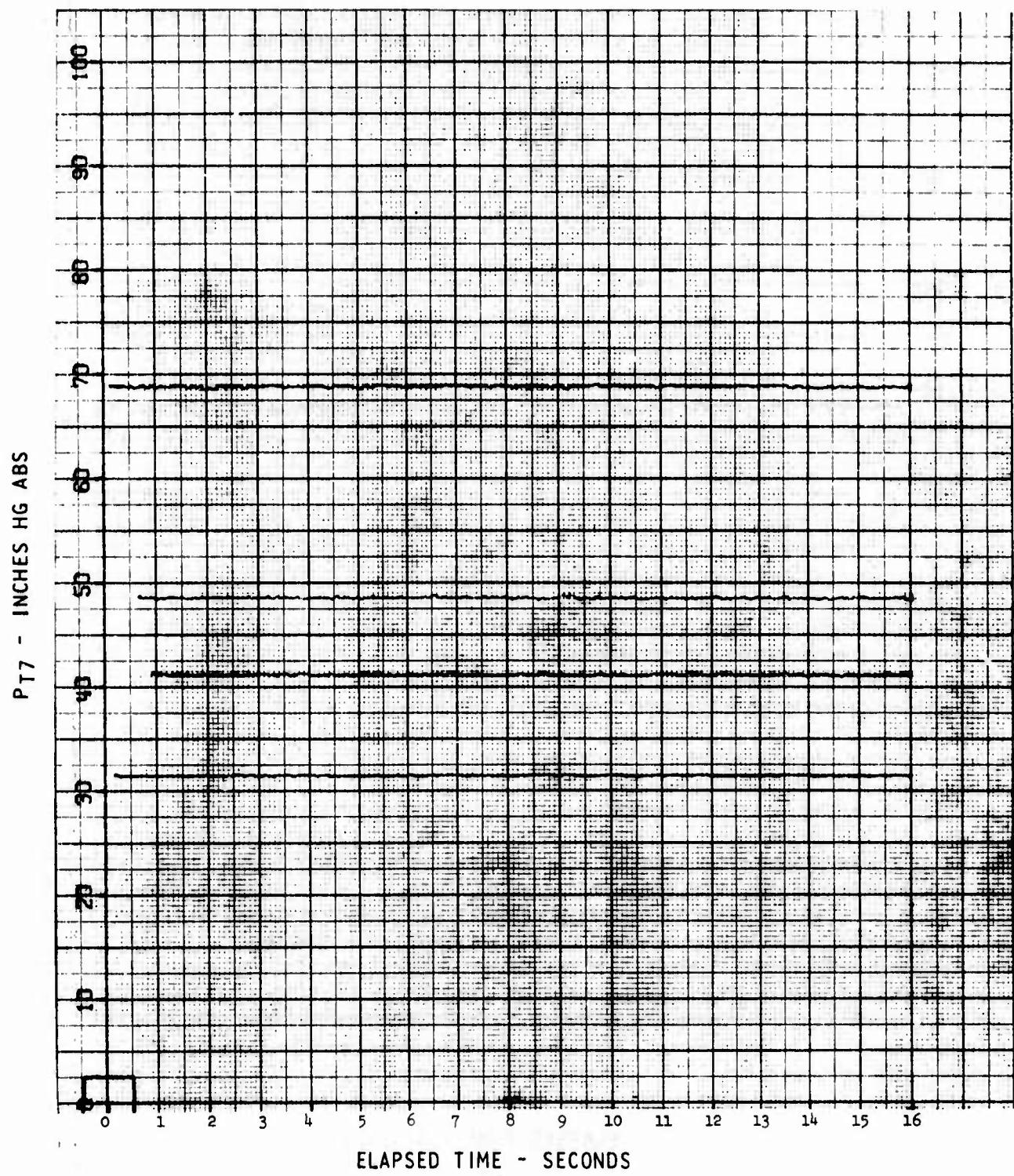


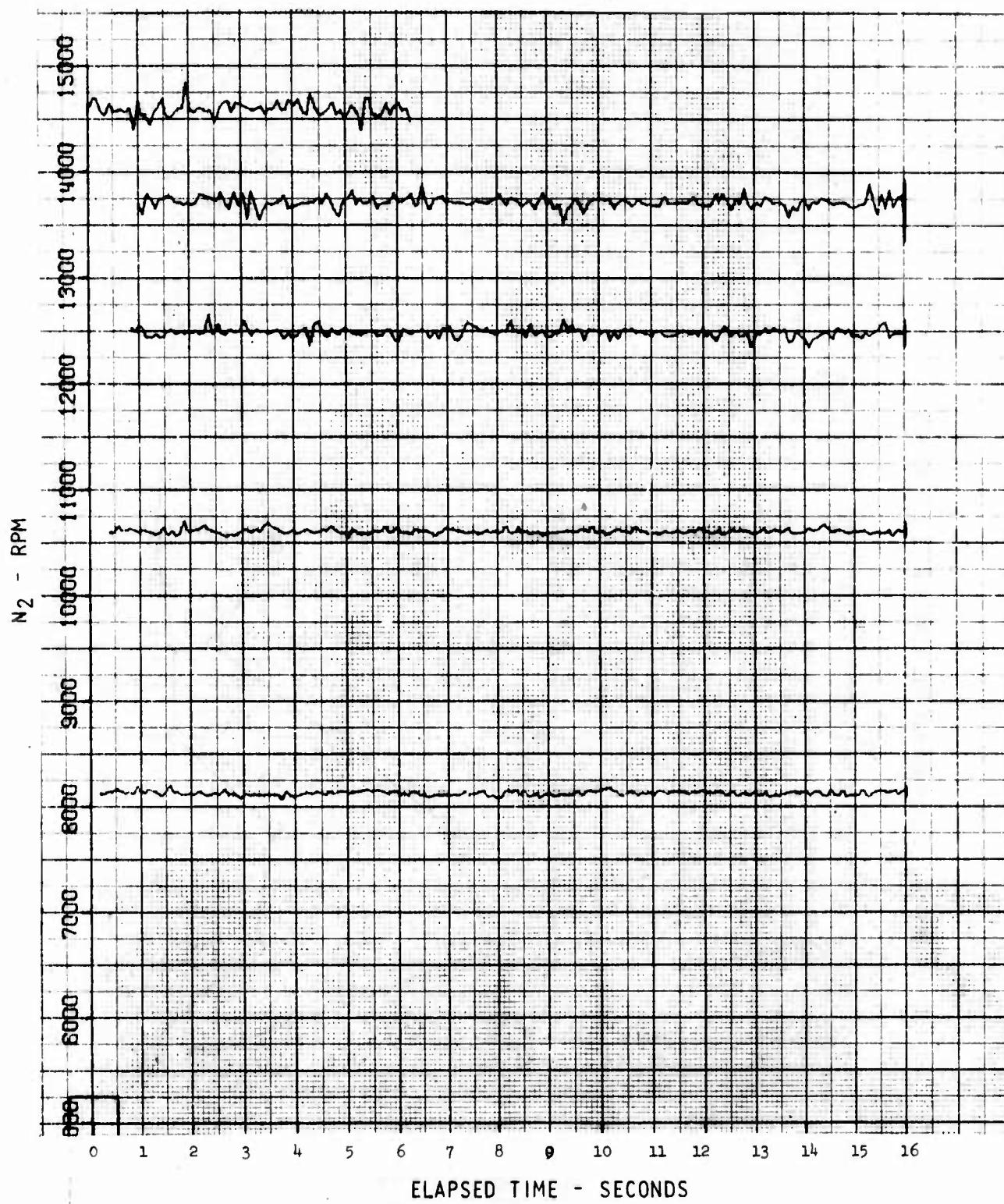
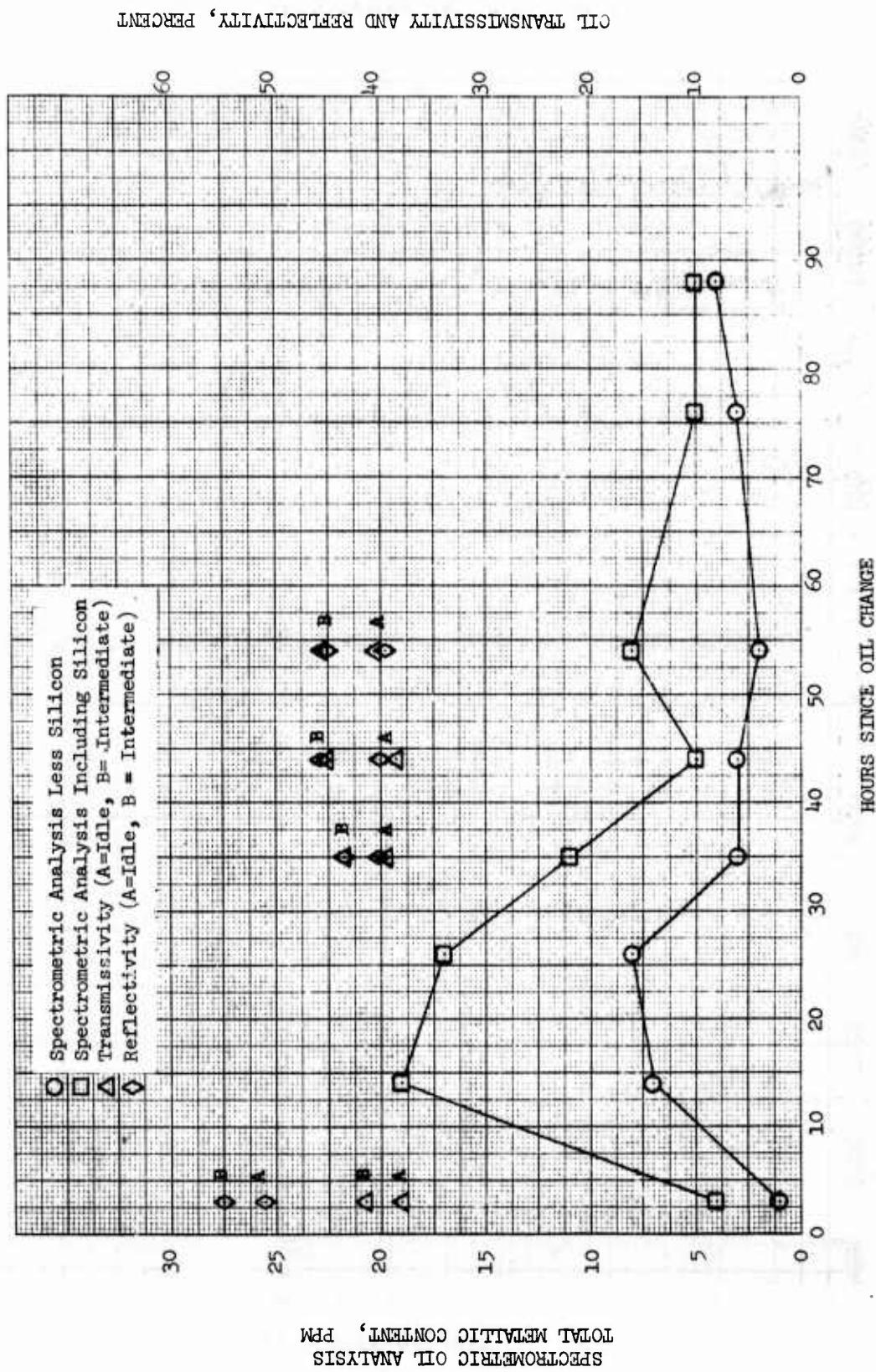
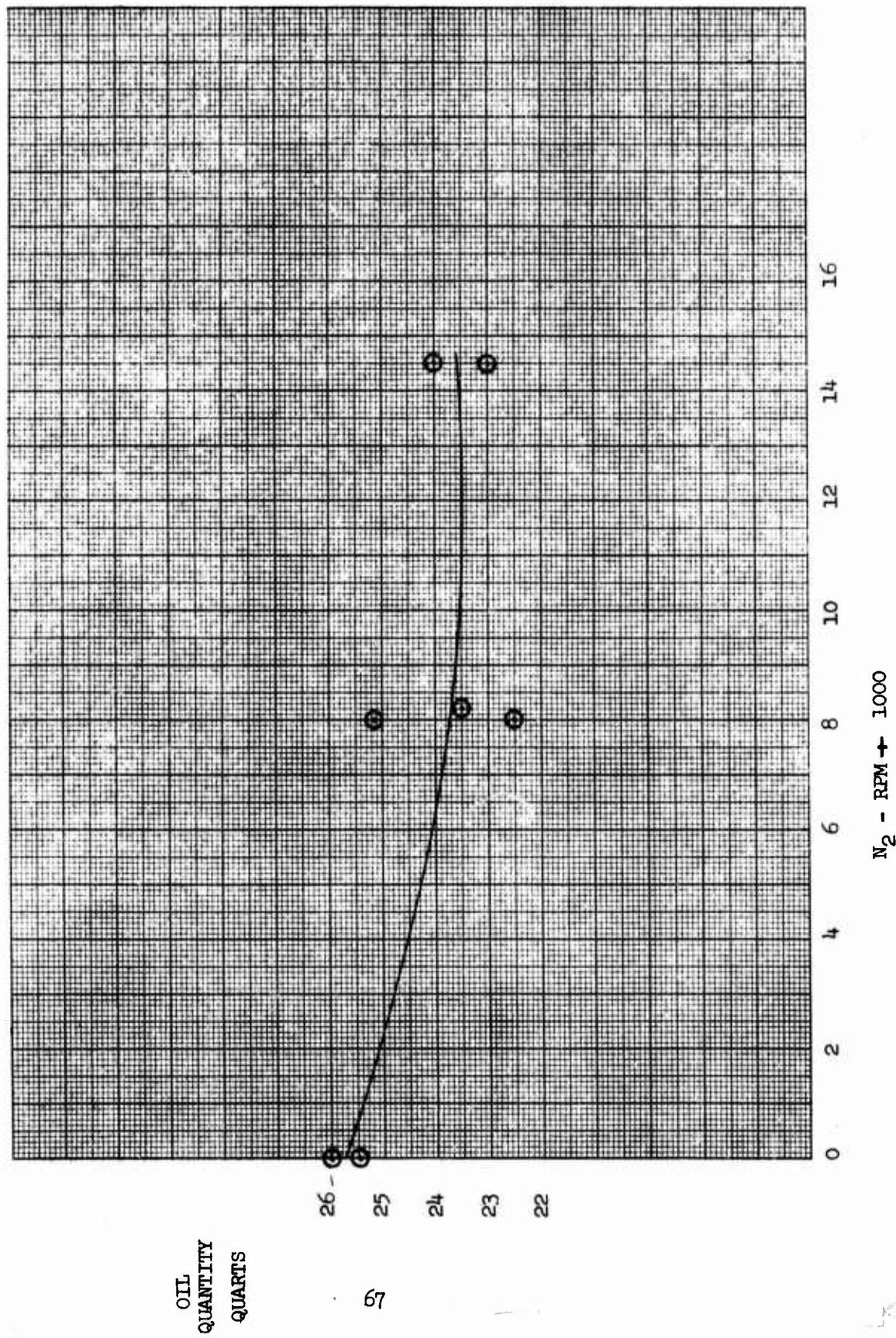
FIGURE 23: N_2 ROTOR SPEED VS TIME

FIGURE 24: SPECTROMETRIC OIL ANALYSIS VS OIL MONITORS



TURBINE ENGINE DIAGNOSTIC DEVELOPMENT

FIGURE 25: OIL LEVEL VS N_2 RPM



LIST OF REFERENCES

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TURBINE ENGINE DIAGNOSTICS DEVELOPMENT PHASE I REPORT,

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2. Work Unit Assignment
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7. Engine Monitoring

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